FUNDAMENTAL CONCEPTS OF

FIBER OPTIC

"The pulse of SPEED is ACTION, like a TRIGGERING a WAVE of LIGHT"

DR. NORHANANI ABD RAHMAN
MOHAMAD ZAMRI MUHAMAD

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We hereby declare that this module is our original work. To the best of our knowledge, it contains no materials previously written or published by another person. However, if there is any, due acknowledgment and credit are mentioned accordingly in the e-book.

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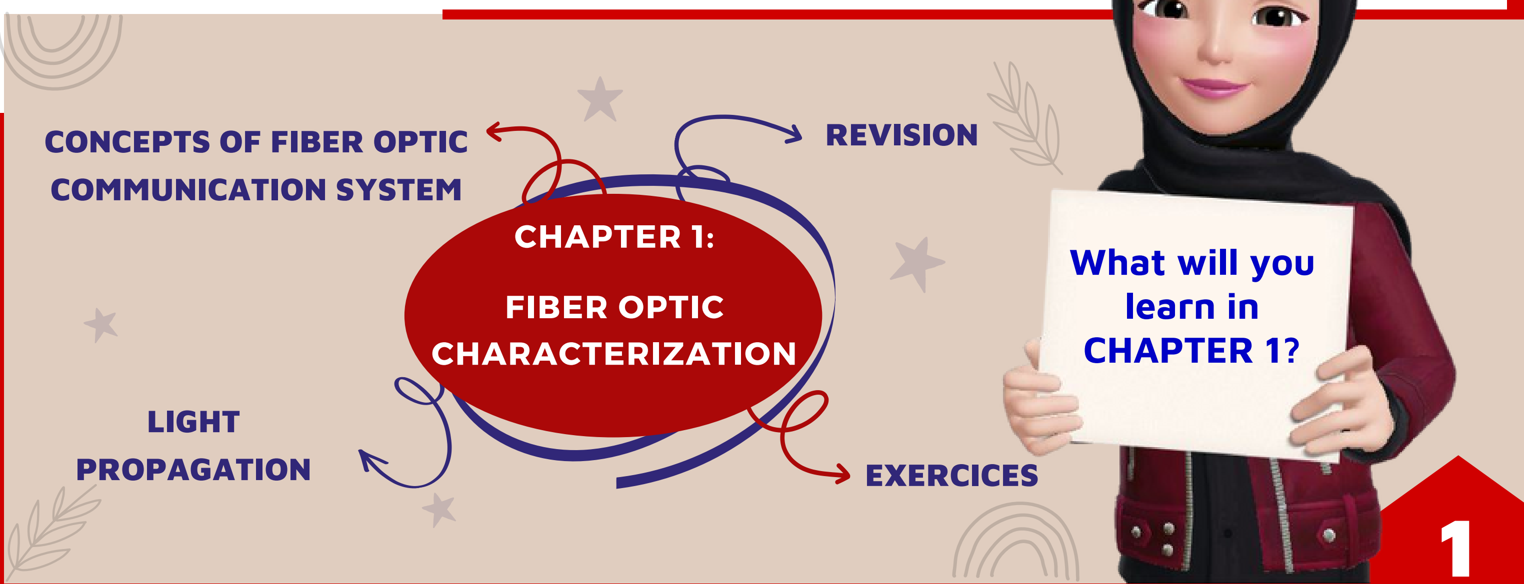
INTRODUCTION

- Optical fibers are constructed of either glass or plastic.
- Most are many kilometers long and have a diameter similar to that of a human hair.
- Light moves through the the fiber from a point to the other and carried out the signal.
- Metallic conductors cannot compete with fiber optic systems in many situations. Their main benefit is bandwidth.
- Since light has a longer wavelength than metal conductors, even coaxial conductors, it is possible to carry a signal with much more information.

- Optical fiber is the **MEDIUM** for transmitting communication signals in the form of light via thin fiber of glass or plastic from one location to another.
- These **SIGNALS** are either digital pulses or continuously modulated analog streams of light that carry information.
- **INFORMATION** - any other kind of data, including voice information, data information, computer information, and video information



CODER / CONVERTER

- Perform an analogue to digital conversion (ADC)
- Input: The coder transforms analogue signals (such as audio, video, and computer data) to digital signals.
- Output: Signals from the computer are sent directly to the light source transmitter circuit.

LIGHT SOURCE

- Utilizing either a Light Emitting Diode, often known as an LED, or a low-intensity laser beam source, such as an Injection Laser Diode-solid state laser, or, in some cases, an infrared beam of light
- The ON/OFF rate of a light source is determined by the frequency of digital pulses.
- Digital signals are transformed into light pulses at one end of fiber-optic cable.

FIBER OPTIC CABLE

- Digital signals, such as audio, video, or computer data, are converted into analogue signals.

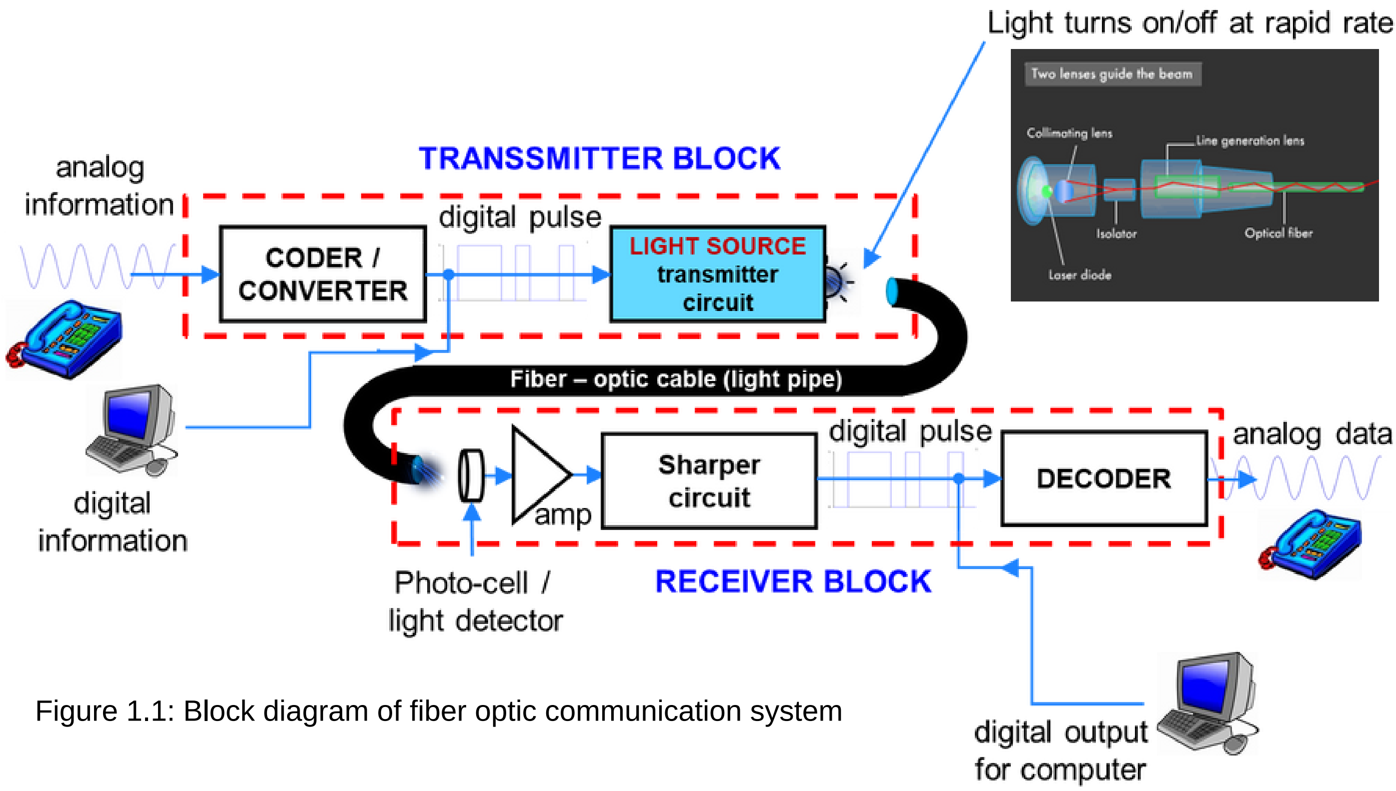


Figure 1.1: Block diagram of fiber optic communication system

LIGHT DETECTOR

- The light pulses are detected and converted into a proportionate electrical signal (Analog signals; such as voice, video or computer data)
- Using the shaper circuit, the electrical signals are generated and converted back to digital pulses.
- The signal may be immediately extracted from the shaper circuit's output if the input signals are digital computer signals.

LIGHT DETECTOR /PHOTODETECTOR

- Light pulses are detected, and the electrical signal is transformed into a proportional signal. audio, video, or digital data signals into analogue signals.
- The shaper then amplifies and reshapes the electrical impulses into the original digital pulses.
- If the input signals are digital, the signal can be extracted directly from the shaper circuit's output.

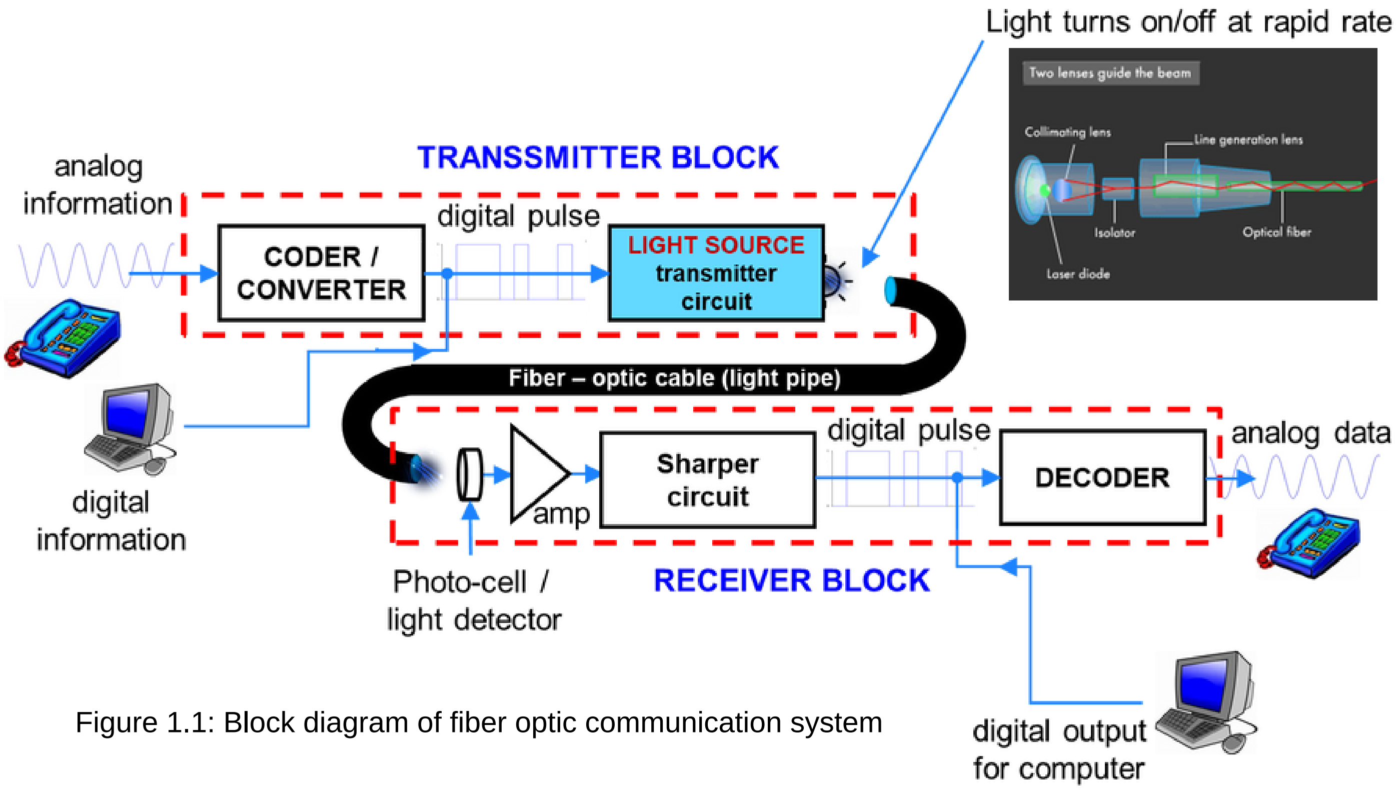


Figure 1.1: Block diagram of fiber optic communication system

DID YOU KNOW?

DECODER

- Light pulses sent to one end of fiber optic cable are transmitted to the other end of the wire.
- Over a long distance, the cable has VERY LESS attenuation, which is the loss of light waves because of the absorption.
- It has a wide bandwidth, so it can carry a lot of information.

ENVIRONMENTAL BENEFIT: FIBER OPTIC CABLE COMPARED WITH COPPER CABLE

- Fiber optic cable needs below than 1 Watt to conduct light pulses over than 300 meter.
- While, the coaxial cables required a 3.5 Watt over 100 meter to transmit the data.

LESS HEAT

- Produced by fiber-optic wires because signal transmission uses less energy.
- Despite this, copper-based data centres need a lot of cooling, which in turn requires a lot of electricity.
- This cooling is unnecessary for fibre networks.

FEWER MATERIALS

- Fiber-optic cables need less materials than copper cables due to two factors.
  - Less insulation and jacketing are required for fiber-optic cable.
  - Copper wires often have a shorter lifetime than fiber-optic cables.
- Fiber has more durability than coper. Due to a longer lifetime, fewer fiber cables are extracted from the ground and discarded.
- Because fiber-optic materials do not need to be constructed and installed as often, less resources are needed.

LESS ENERGY

- Performance and reliability - Fiber-optic cable are better than copper cable in terms of performance and reliability.
- Use less energy than copper while transmitting more data.
- Using fiber optics has a lower impact on the environment, both in the short term and in the long term.
- Carbon dioxide emissions may be lowered as well by using less energy.

SDG:ENVIRONMENT & SUSTAINABILITY

Three reasons why fiber-optic technology can be considered a “green” technology

LIGHT FREQUENCY

- The electromagnetic spectrum is a continuous range of sizes, frequencies, and energy for light waves.
- The light spectrum is the range of wavelengths produced by a light source.
- Nanometers (nm) are the units of measurement for light.
- Each nanometer is a light wavelength or band of light energy. The visible light spectrum ranges from 380nm to 780nm.

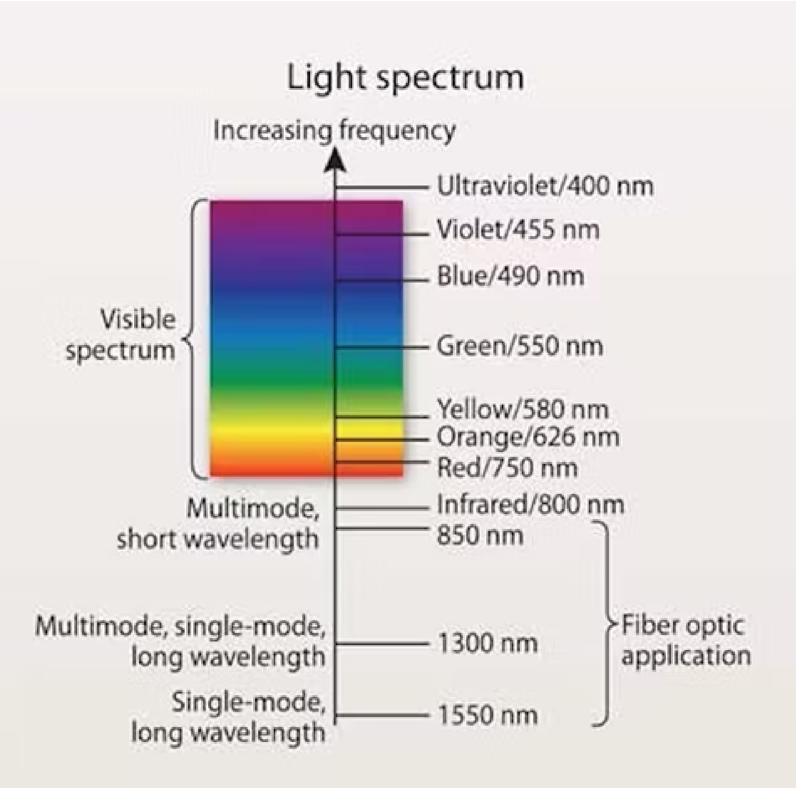
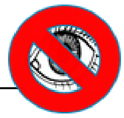


Figure 1.2: Light Spectrum

ULTRAVIOLET

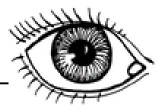


Too short a range of light wavelengths for human vision.

INFRARED

Human eyes are unable to see light wavelengths that are too long to be seen.

VISIBLE



The range of light wavelengths to which the human eye will react.

DID YOU KNOW?

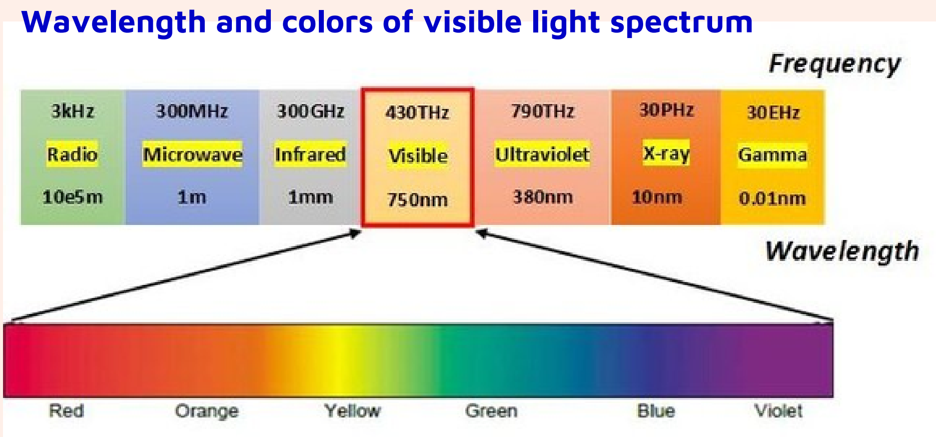


Figure 1.3: Visible Light Spectrum

CONCEPTS OF LIGHT PROPAGATION

- Propagation of light refers to the ways in which an electromagnetic wave transfer it's energy from one point to another.
- Three main processes generally occur when light passes between boundaries are:
  - Reflection
  - Refraction
  - Diffraction
- WAVELENGTH is an IMPORTANT PARAMETER in fibre optics communication systems.
- This takes us to TWO (2) key concepts: WAVELENGTH AND PERIOD.

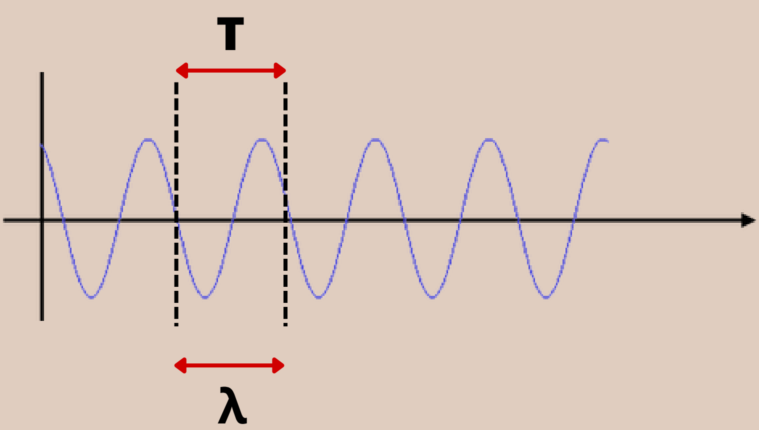
WAVELENGTH

DISTANCE between **TWO IDENTICAL POINTS** (the points having the same phase) of **TWO** successive **CYCLES** of the **WAVE**.

PERIOD

TIME it takes a **WAVE TWO IDENTICAL POINTS** (the points having the same phase) to pass, **IN SEQUENCE, THE SAME SPACE LOCATION.**

IMPORTANT PARAMETER



$$c = \frac{\lambda}{T}$$

Where;

c = speed of light (m/s)

λ = wavelength (m)

f = frequency (Hz)

since f = 1/T

The speed of light in free space is $c = 3 \times 10^8$ m/s

REFRACTION

- When a light wave enters a medium with a different velocity of propagation (the speed at which waves may move through a medium), the wave's direction will change.

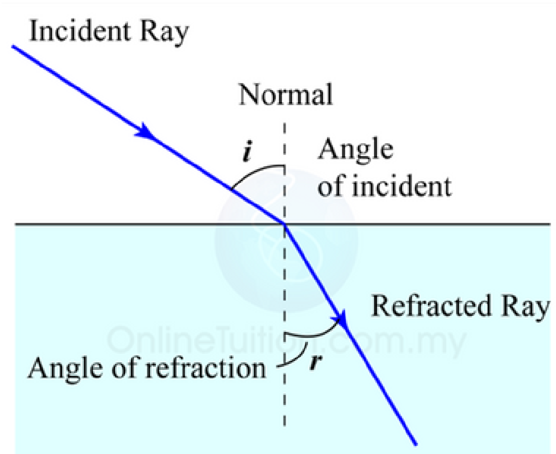


Figure 1.4: Refraction of light

REFLECTION

- Reflection is the process by which a signal is redirected back into its original medium after changing directions at an interface between two separate media.
- The angle of incidence is equal to the angle of reflection (from the reflective ray to the normal).

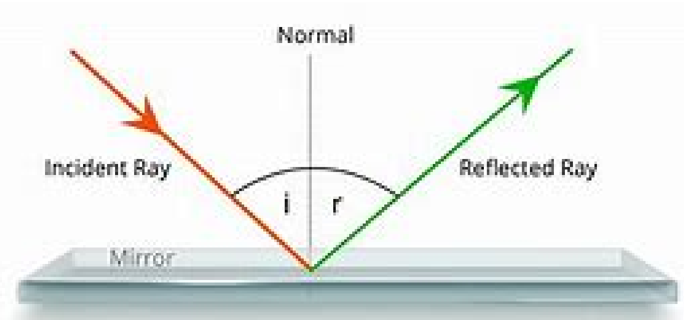


Figure 1.5: Reflection of light

DIFFRACTION

- Light waves have a tendency to bend and spread at oblique angles when they are close to a barrier.
- This phenomenon is known as light diffraction, and it happens when a light wave travels extremely near to the edge of an object or through a small hole, such as a slit or aperture.
- Diffraction is the small bending of light as it passes by an object's edge.

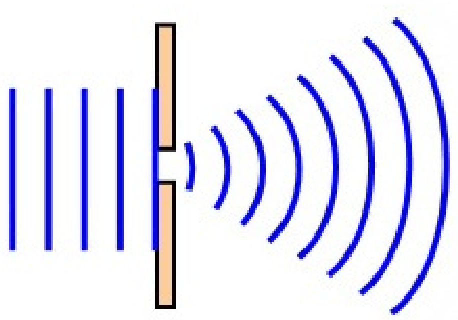
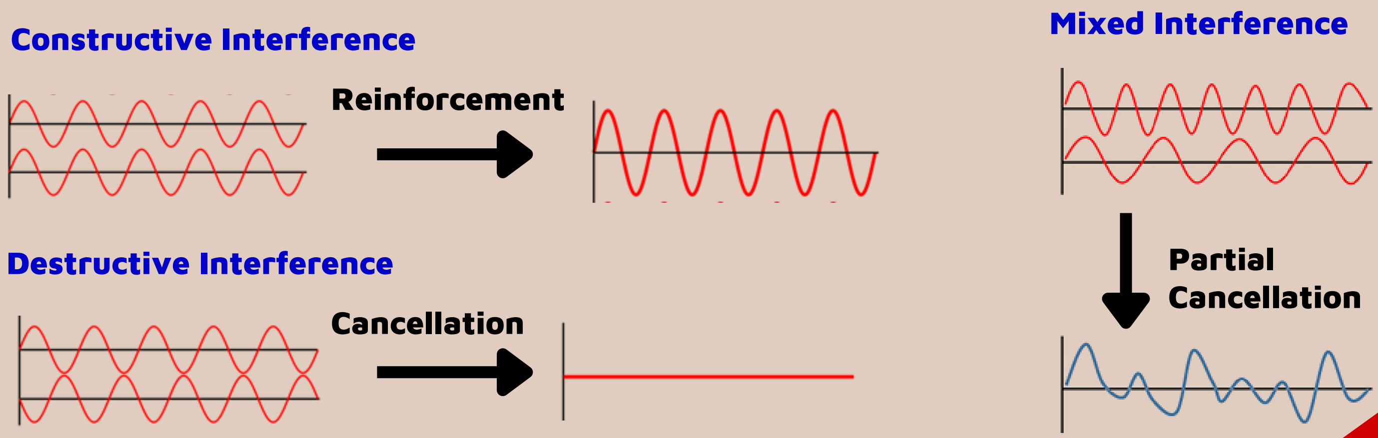


Figure 1.6: Diffraction of light

DID YOU KNOW?



TERMS IN LIGHT PROPAGATION

- Light propagation describes how light moves in a straight line.
- Light that goes through a glass is bent, so it doesn't go in a straight line.
- When light bounces off of a smooth surface, this is called light reflection.

INDEX OF REFRACTION

Index of refraction (n) is the ratio of the speed of light in a vacuum to the speed of light in a medium (v).

$$n = \frac{c}{v}$$

n = refractive Index
c = speed of light in vacuum/air
v = speed of light in medium

SNELL´S LAW OF REFRACTION

The angle of incidence and the angle of refraction are connected when light moves from a material with one index of refraction to a materials with a different index of refraction.

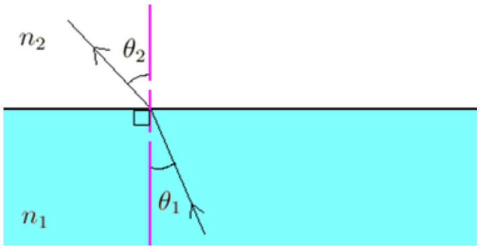
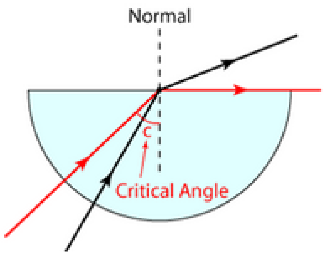


Figure 1.7: Refraction of light in Snell's law

CRITICAL ANGLE

The maximum angle at which a beam of light in one transparent media may contact the border with a second with a lower refractive index without being totally reflected in the first medium.



$$\theta_c = sin^{-1}\frac{n_2}{n_1}$$

Figure 1.8: Critical angle in refraction of light

Snell's Law

$$n_1\, sin\theta_1 = n_2\, sin\theta_2$$

Where :
n1 = refractive index for material 1
n2 = refractive index for material 2
sinθ1 = angle of incidence
sinθ2 = angle of refraction

Refraction to Reflection LIGHT

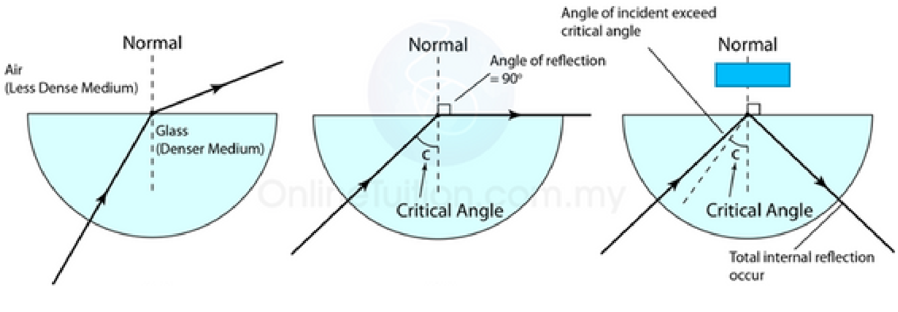


Figure 1.9: Refraction to Reflection of light

1. The light refracts away from the normal if the incidence angle is smaller than the critical angle.
2. When the incidence angle equals the critical angle, light refracts at 90 degrees to the normal.
3. Total internal reflection occurs when the angle of incidence is larger than the critical angle.

TERMS IN LIGHT PROPAGATION

$n_1 \sin\theta_1 = n_2 \sin\theta_2$

Substitute $\theta_2 = 90°$

$n_1 \sin\theta_1 = n_2 \sin(90)$
$n_1 \sin\theta_1 = n_2 (1)$

When $\theta_2 = 90°$, θ_1 become the critical angle, θ_c
$n_1 \sin c = n_2$

The equation for the critical angle, θ_c becomes:

$$\theta_c = \sin^{-1}\frac{n_2}{n_1}$$

TOTAL INTERNAL REFLECTION

- Internal reflection of light at the interface of two different transparent materials.
- At an angle greater than the critical angle, the light is really reflected back into the first material from the boundary.

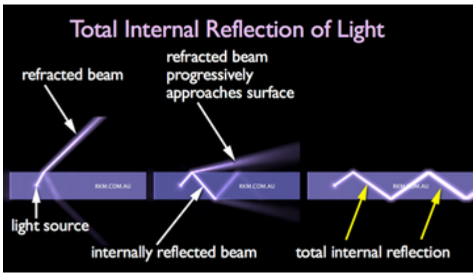


Figure 1.10:Total internal reflection of light

NUMERICAL APERTURE (NA)

- A way to measure how much an optical fibre can capture light.
- As the greatest acceptable angle for light transmission via an optical fibre

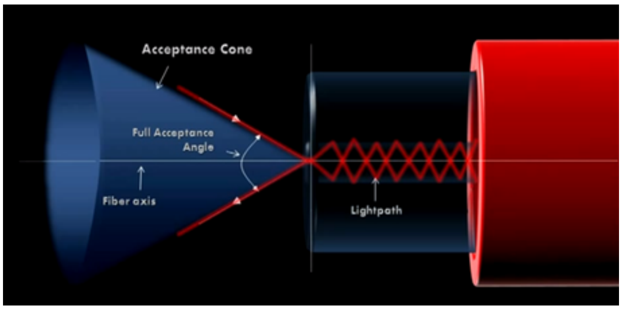


Figure 1.11: Light outside the acceptance cone

$$NA = \sqrt{n_1^2 - n_2^2}$$

ACCEPTANCE ANGLE

- The angle at which light may be received by an element, such as a detector or a waveguide.
- Also used to describe the acceptance cone of an optical fiber.

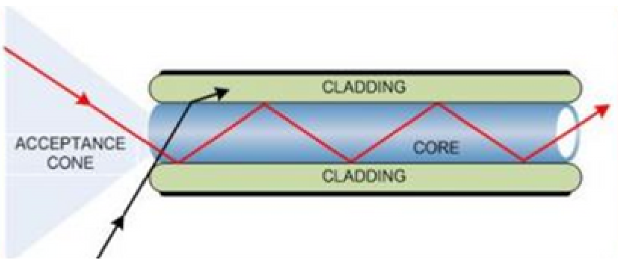


Figure 1.12: Acceptance angle of light

$$acceptance\ angle = \sin^{-1} NA$$

EXAMPLE 3.1:

Diamond's index of reflection is 2.419, but the speed of light in a vacuum is 2.99 x 10^8 m/s. In the material, how can I determine how fast light travels?

SOLUTION:

$$n = \frac{c}{v} \rightarrow 2.419 = \frac{2.99 \text{ x } 10^8}{v}$$

$$v = 1.236 \; x \; 10^8 \text{m/s}$$

EXAMPLE 3.2:

A vacuum's velocity is 2.99 x 10^8 m/s, whereas the water velocity of light is 2.248 x 10^8m/s, hence the difference between the water and vacuum speeds of light is negligible. What is the material's refraction index?

SOLUTION:

$$n = \frac{c}{v} \rightarrow n = \frac{2.99 \text{ x } 10^8}{2.248 \text{ x } 10^8}$$

$$n = 1.019$$

EXAMPLE 3.3:

According to these values, the light speed in vacuum equals 2.99 x 10^8m/s, whereas the index of reflection of diamond is 2.420, benzene 1.501, and crystallised quartz is 1.544. All three materials may be used to calculate the speed of light

SOLUTION:

DIAMOND

$$2.419 = \frac{2.99 \text{ x } 10^8}{v}$$

$$v = \frac{2.99 \text{ x } 10^8}{2.419}$$

$$v = 1.236 \; x \; 10^8 \text{m/s}$$

BENZENE

$$1.501 = \frac{2.99 \text{ x } 10^8}{v}$$

$$v = \frac{2.99 \text{ x } 10^8}{1.501}$$

$$v = 1.992 \; x \; 10^8 \text{m/s}$$

CRYSTALLISED QUARTZ

$$1.544 = \frac{2.99 \text{ x } 10^8}{v}$$

$$v = \frac{2.99 \text{ x } 10^8}{1.544}$$

$$v = 1.937 \; x \; 10^8 \text{m/s}$$

Fiber Optic Characterization

Block Diagram of FO System

- Coder / Converter
- Decoder
- Light Source
- Light Detector
- Fiber Optic Cable

Environmental Benifits

- Less heat
- Fewer Materials
- Less Energy

Light Propagation

- Refraction
- Reflection
- Diffraction

Terms in Light Propagation

- TOTAL INTERNAL REFLECTION
- ACCEPTANCE ANGLE
- NUMERICAL APERTURE (NA)
- SNELL'S LAW OF REFRACTION
- CRITICAL ANGLE
- INDEX OF REFRACTION

IMPORTANT FORMULA

INDEX OF REFRACTION

$$n = \frac{c}{v}$$

CRITICAL ANGLE

$$\theta_c = sin^{-1}\frac{n_2}{n_1}$$

NUMERICAL APERTURE (NA)

$$NA = \sqrt{n_1^2 - n_2^2}$$

SNELL'S LAW OF REFRACTION

$$n_1 \, sin\theta_1 = n_2 \, sin\theta_2$$

ACCEPTANCE ANGLE

$$acceptance\ angle = sin^{-1}NA$$

EXERCISE 1.1:

Determine the refraction angle at the air/core contact, the critical angle, and the incident angle at the core/cladding interface. Will this light ray go the length of the fiber?

n air = 1
n core = 1.46
n cladding = 1.43
incident angle = 12°

EXERCISE 1.2:

The core diameter of a step index fiber is 150m, and the refractive index is 1.4. The refractive index of the cladding is 1.3.

Determine the numerical aperture of the fiber as well as the acceptance angle from air.

EXERCISE 1.3:

Since the index of reflection of glass is 1.523 and the index of reflection of air is 1, Find the acceptance angle if the light is coming from the air and moving towards the glass.

EXERCISE 1.4:

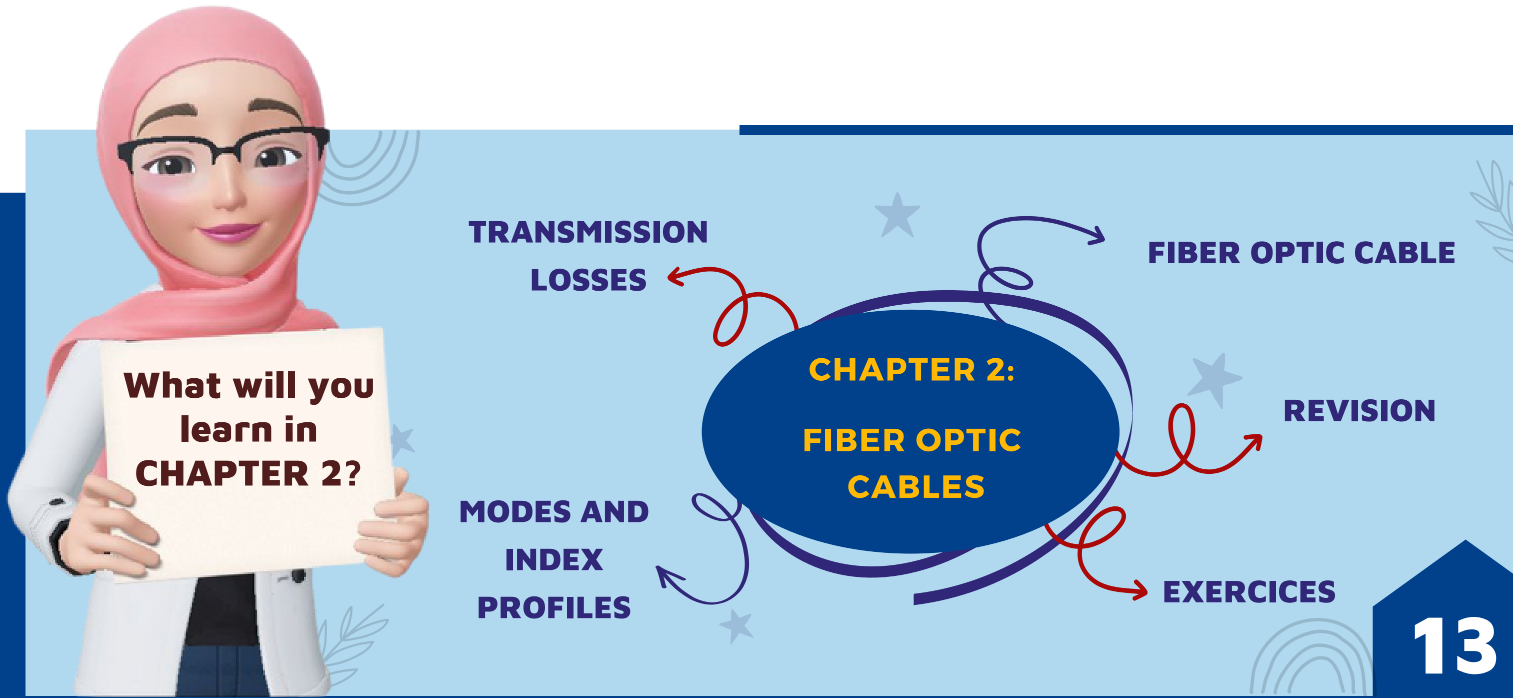
Calculate critical angle equations using the Snell's law provided; next determine its critical angle if density of medium 1 is 1.45 and density of medium 2 is 1.37.

EXERCISE 1.5:

Calculate : The Angle of Refraction, NA and Acceptance Angle if
Material 1 Glass, n = 1.5
Material 2 Quartz, n = 1.38
Angle of Incidence = 350

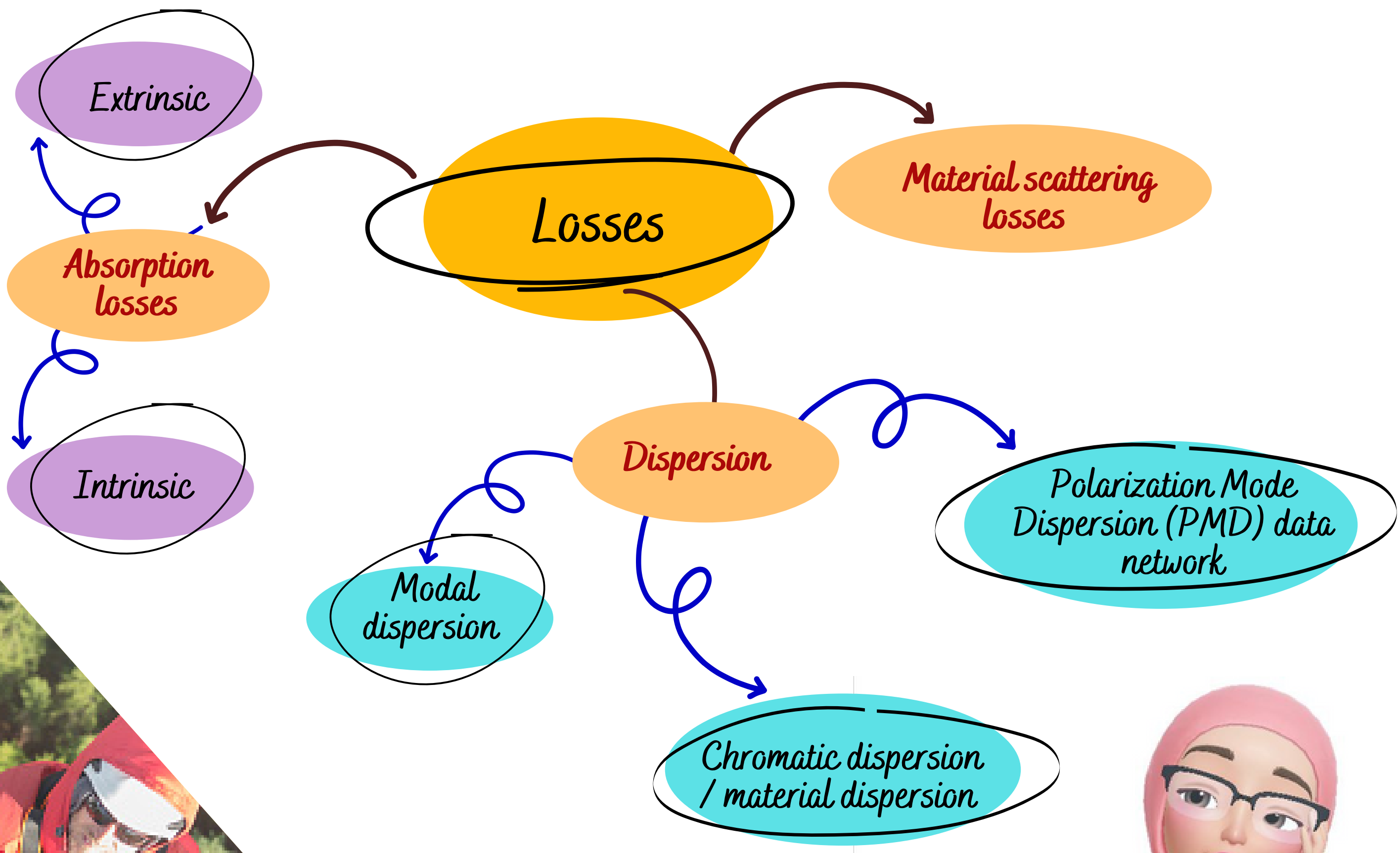
INTRODUCTION

- Long-distance and high-performance data networking are made possible by fiber optics.
- The internet, television, and telephones are all forms of telecommunication that utilize it often.
- Other sectors, such as the medical, military, government, industrial, and commercial ones, also employ it.
- Data is sent across fiber-optic cables using light pulses that move fast.
- A second glass layer, referred as as the "cladding," is wrapped around the center fiber and allows light to constantly bounce off the walls of the cable rather than seep out at the edges, allowing the single to travel farther without attenuation.
- Fiber optic cables come in single-mode and multimode varieties.
- Because multimode fiber has different optical characteristics at the core, it may transmit numerous light beams (modes) at once.
- The core size of single-mode fiber is substantially smaller (9 microns).



TRANSMISSION LOSS (TL)

- A wave's cumulative loss in strength as it moves away from its source, via a specific region or through a specific kind of structure is known as transmission loss (TL).
- The optical power of a signal can only go so far in a fiber before it loses enough strength to be recognized due to transmission loss. It gauges how much light is lost between the source and the output, and it's often stated in decibels (dB).
- Attenuation - reduction of the optical signal intensity over a length of optical fiber / components. It measured in two instances:
  - **Fiber attenuation** - decibels per kilometer (dB/km) [absorption and scattering]
  - **Component attenuation** (in dB loss) for splitters/couplers, WDMs, connectors, both mechanical and fusion splices, etc.
- Three types of losses in fiber optic:



ABSORPTION LOSSES

- Due to optical power being converted into heat, some of the attenuation occurs.
- Fiber attenuation of 3% to 5%.
- By limiting the quantity of contaminants used in the production process, it may be kept below acceptable limits.

INTRINSIC

- The fundamental features of fibers it is because of material and electron absorption:
- Some of the optical power delivered via the optical fiber is converted into heat by material absorption, a loss process that occurs at roughly 0.03 dB/km.
- Intrinsic absorption in the ultraviolet induced by electronic absorption is known as electron absorption. When a photon (light particle) interacts with an electron and raises its energy level, this is known as excitation.
- Glass fibers are suitable for long-distance communications because of their low absorption.
- Glass and dopant chemicals should be used to eliminate impurities in order to reduce intrinsic absorption.

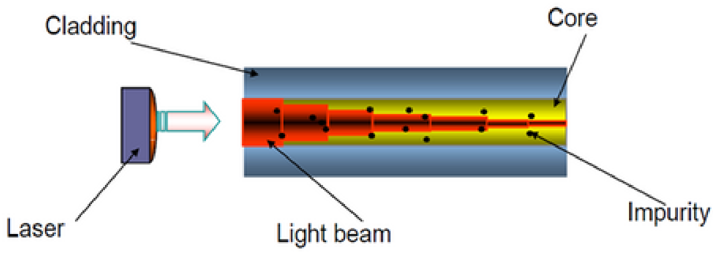
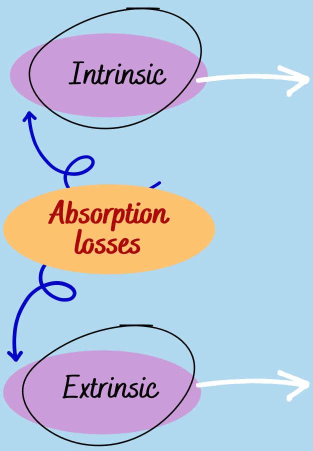


Figure 2.1: Intrinsic absorption cause of impurities in core fiber

EXTRINSIC

- During the manufacturing process, fiber optic cables may include undesirable particles or contaminants such as iron, nickel, or chromium optical fibers.
- Also happens when hydroxyl ions (OH), which are caused by the presence of water vapor, are brought into the fiber.
- Natural glass imperfections absorb the light signal.

DID YOU KNOW?



- Cause of the fiber impurities
- When a light beam hits an impurity, some of its energy is reflected back from the contaminant and some of it is absorbed.

- Contaminants during the manufacturing process

MATERIAL SCATTERING LOSS

- One or more localized nonuniformities in the material that light is passing through cause it to deviate from a straight path, which is known as scattering.
- Light scattering generated by changes in density inside a fiber and their interaction with light.
- When optical fibers are fabricated, contaminants like dust and air bubbles cause density variations.
- Dilute reflections are another name for them.
- Light from the core is scattered via Material Scattering.

Rayleigh Scattering Loss

- 96% of optical fiber attenuation is due to Rayleigh scattering (for both regions mentioned before).
- Rayleigh Scattering decreases as wavelength increases.
- There is a greater scattering of light at shorter wavelengths than at longer ones. Rayleigh scattering makes it impossible to utilize light at wavelengths less than 800 nm for optical communication.
- Improved fabrication and production may minimize material scattering.
- Scattering - ray hits an impurity and part of it is reflected in the fiber.

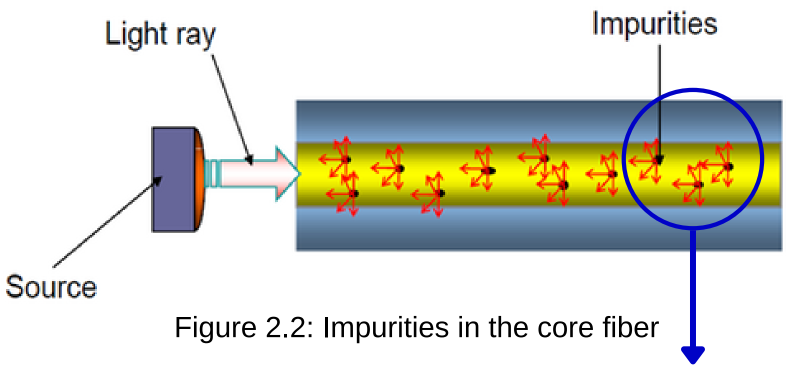


Figure 2.2: Impurities in the core fiber

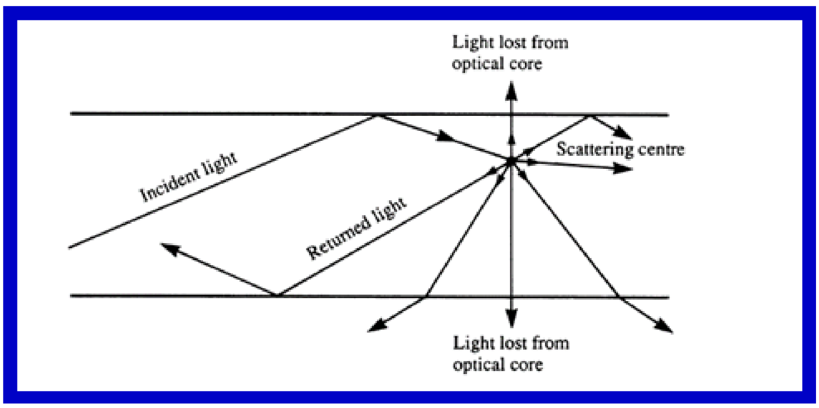


Figure 2.3: Impurities in the core fiber produce light scattering.

DISPERSION

- The spread of the optical pulse as it travels along the fiber.
- If the signal pulse rate is too fast, dispersion will cause the pulses to overlap, leading to distortion.
- Dispersion is caused by two basic factors: differential source wavelengths and modes.
- The number of modes supported by the fiber must be minimized to reduce dispersion distortion. This is accomplished by lowering the diameter of the core.
- The spread of the optical pulse as it travels along the fiber limits the speed with which information may be conveyed.

MODAL DISPERSION / INTERMODAL DISPERSION

- Various modes (paths) across the fiber take different times.
- This occurs only in multimode fiber, limiting its performance.
- Modal dispersion will be reduced as the length of the fiber increases using graded-index fiber.

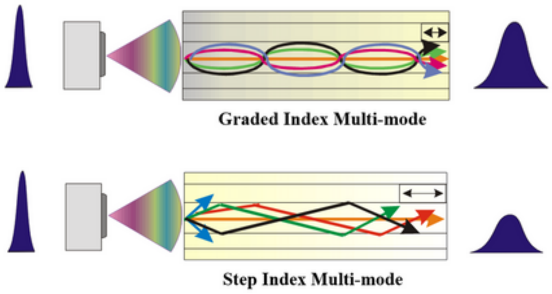


Figure 2.4: Comparison graded and step index multimode

CHROMATIC DISPERSION / INTRAMODAL DISPERSION

- Fibers transmit various wavelengths of light at different speeds via different materials.
- Fibers of both single-mode and multimode are affected.
- LEDs have a greater impact than lasers.
- Modal dispersion has a far lesser impact on a study's results.
- A 'dispersion compensator' may be used to eliminate the dispersion that occurs when the pulse travels down the fiber, as indicated in the figure.
- To ensure accurate decoding by the electronics, a specially prepared length of fibre is used to produce dispersion opposite to that caused by the transmission fiber.

POLARIZATION MODE DISPERSION

- There are differing speeds for light that travels in different directions in fibers that aren't entirely symmetric.
- If the cable is stressed or the circular shape is incorrect, there is no straightforward method to fix it.
- Both single mode and multimode fibers may be affected by this dispersion.
- It is possible to convey two distinct polarizations of the same transverse mode in a single-mode fiber, despite the fact that the fiber can only support one transverse mode.

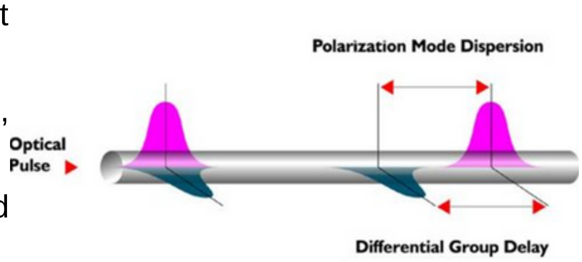


Figure 2.5: Polarization mode dispersion

- Some of the digital pulse's light rays may go in a straight line because of the big core, while others may zigzag as they bounce off the cladding. When light travels in multiple directions, it is known as mode, and each mode arrives at the receiving point in a separately.
- Two propagation modes of fiber-optic cable:
  - Single mode
  - Multimode

SINGLE MODE

- Light can only go through it in one direction and one mode at a time
- An 8-10 micron-diameter glass fiber core forms the core of this single-strand glass fiber.
- Long distance over 5km (50 times as far as multimode)
- Higher rate of transmission
- Offers much improved performance with less attenuation.
- Really hard to work with and very expensive.

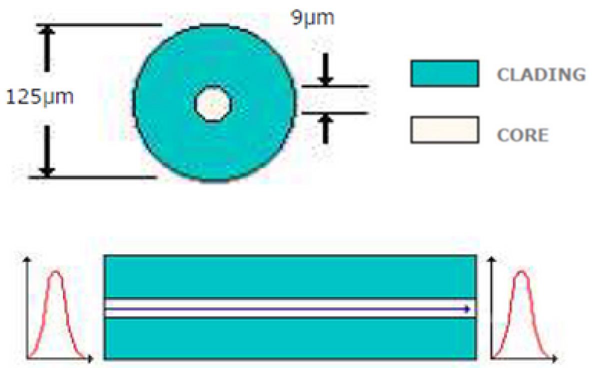


Figure 2.6: Characteristics and transmission of single mode

MULTI MODE

- Multimode fiber provides large bandwidth across medium distances at high speeds.
- As light waves pass through the center of the cable, they are scattered into multiple paths, or modes.
- There are two varieties in use: 50/125 and 62.5/125.
- LEDs are used to transmit data.
- The wavelength range is 850 to 1300 nm.

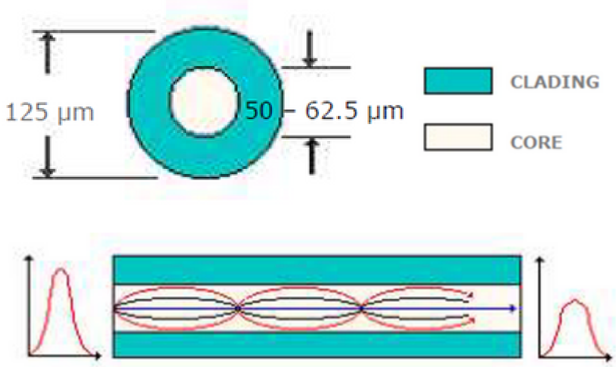


Figure 2.7: Characteristics and transmission of multi mode

DID YOU KNOW?

MODES

Single Mode — **Wavelength, λ : 1310nm - 1550nm**

Multi Mode — **Wavelength, λ : 850nm - 1300nm**

STEP INDEX

- The cladding has a lower refractive index because of the step-index profile.
- It has a constant refractive index throughout the core and a significant change in refractive index at the core-cladding interface.

GRADED INDEX

- A refractive index profile in which the core's refractive index drops with increasing radial distance from the fiber axis.
- Due to the difference in refractive indices, light beams follow sinusoidal patterns through the fiber as they approach the fiber axis.
- The center of the fiber has a lower refractive index when seen from the outside.
- As the rays go through the lower index of refraction, they bend inside and move quicker.

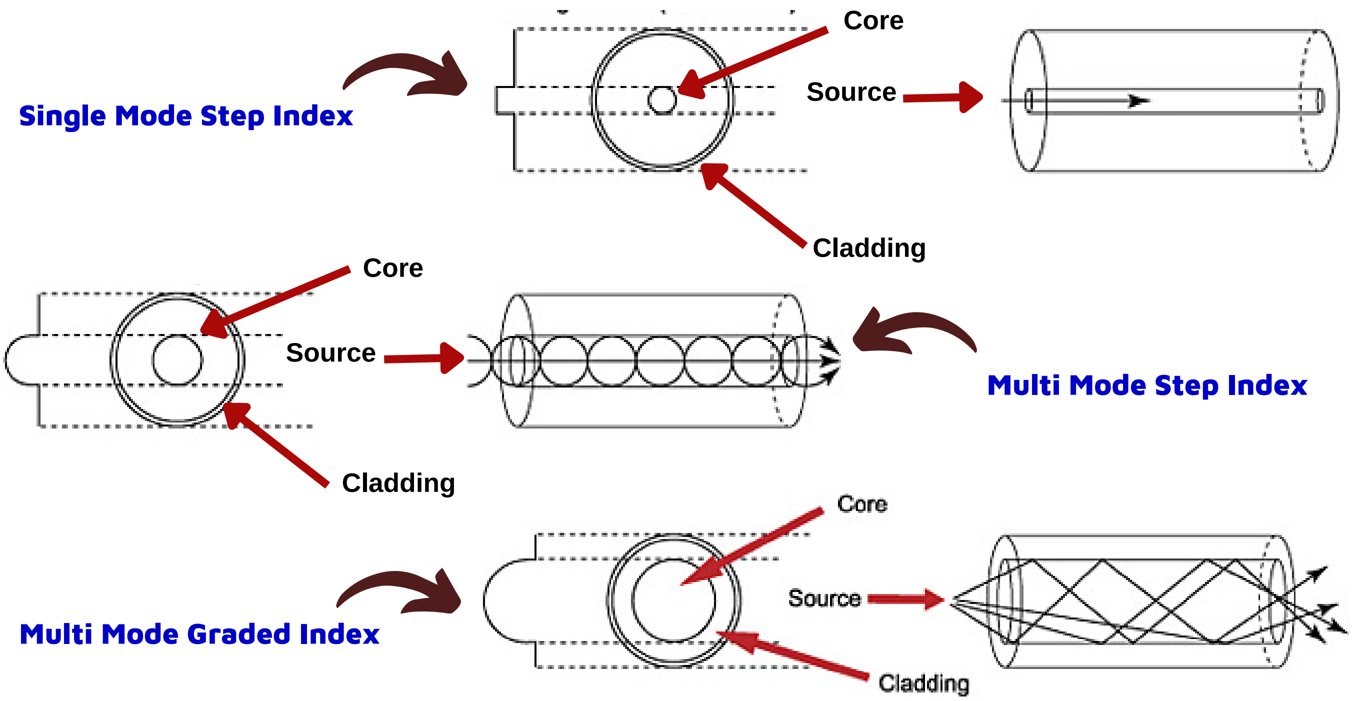
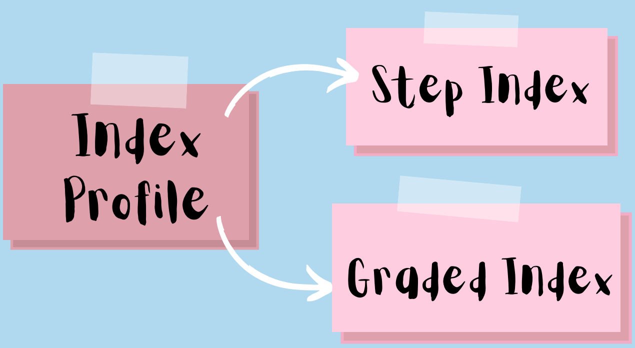


Figure 2.8: Light propagation in single and multimode

DID YOU KNOW?



- A network cable with glass fiber strands inside of an insulated jacket is known as a fiber optic cable.
- Higher bandwidth and longer data transmission lengths are provided via fiber optic lines.

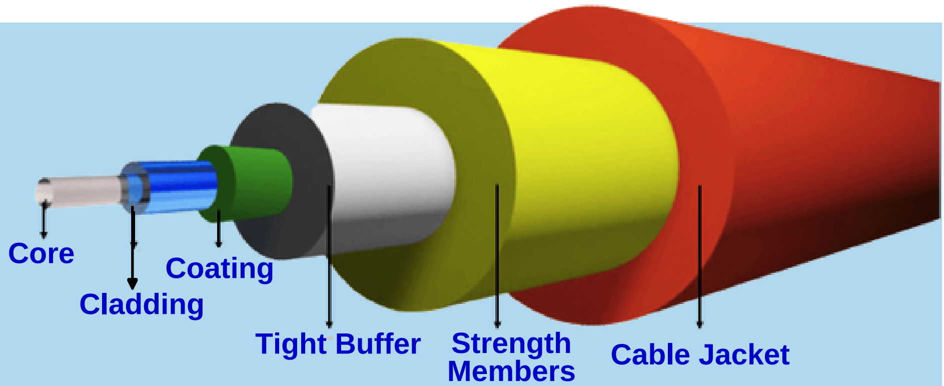


Figure 2.9: Fiber cable structure

CORE

- The "core" of the fiber is where the light travels.
- The optical property of index of refraction, which measures the speed of light in the material, is intended to have a larger value in the core.

CLADDING

The light is trapped in the core using an optical method known as 'Total Internal Reflection,' which surrounds the core with reflective material.

BUFFER COATING

support in damage prevention for the core and cladding

STRENGTH MATERIAL

Preventing the fiber cable from stretching when it is being pulled.

JACKET

is added to protect against abrasion, solvents and other contaminants.

How to choose the adequate fiber type?

DID YOU KNOW?

Table 2.1: Application of fiber cables

Application	Multimode				Single mode	
Light Source	LED or VCSEL				LASER	
Structure	62,5/125	50/125			9/125	
Fiber quality	OM1	OM2	OM3	OM4	OS1	OS2
TRANSMISSION LENGTH PER APPLICATION						
100 Base SX	2 000 m	2 000 m	2 000 m	2 000 m		
1000 Base SX	220 m	550 m	550 m	550 m		
1000 Base LX	550 m	550 m	1 000 m*	1 000 m*	2 000 m	5 000 m
10 G Base SX	32 m	86 m	300 m	500 m		
10G Base LW	220 m	220 m	220 m	220 m	2 000 m	10 000 m
40 G Base SR4			100 m	125 m		
100G Base SR4			100 m	125 m		

TIGHT-BUFFERED CABLE

- Excellent mechanical and environmental protection with one fiber per buffer.
- Tight-buffered cable structure and aramid strength components offer superior cable protection without gel filling.
- No gel required, simple to handle, install, and terminate, saving time, money, and dependability.
- No rigid strength part, flexible wire — easy to handle.
- "Tight-bound" cable may be bent or hung vertically (no fiber axial migration).
- No splicing or breakout kits needed.
- Reduced installation expenses.

LOOSE-TUBE CABLE

- Multifiber buffer.
- Gel filling prevents tube moisture.
- Cleaning gel filling is nasty, expensive, and time-consuming.
- Stiff cable strength member is harder to handle and install.
- Not to be hauled around several bends or hung vertically (fiber axial migration)
- Breakout kits or splicing needed – time consuming, costly equipment Hard to terminate, requiring breakout kits or splicing – time-consuming, costly equipment, and expertise.

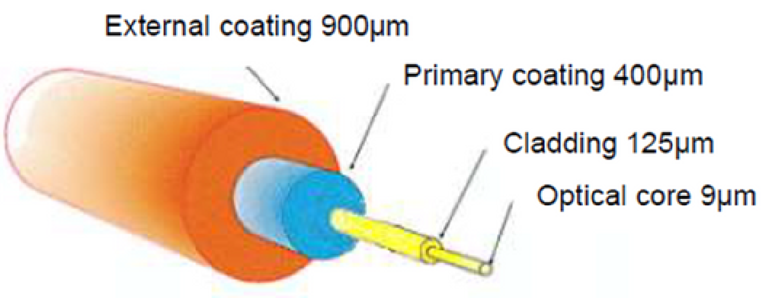


Figure 2.10: Tight buffered cable structure

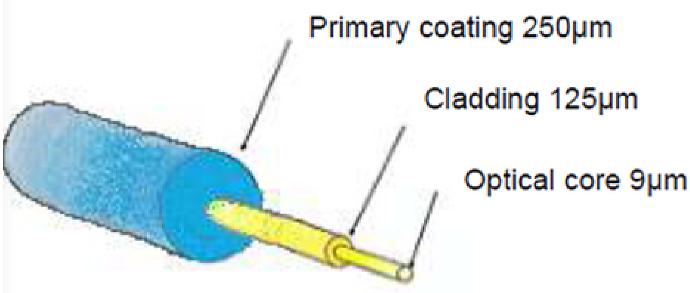


Figure 2.11: Loose tube cable structure

Table 2.2: Comparison between tight buffered and loose tube cables

Tight-Buffered Cable	Loose-Tube Cable
One fiber per buffer	Multiple fibers per buffer
No gel filling needed	Gel filling needed to prevent moisture collection in tubes
No cleaning needed — no gel, easy to handle, install and terminate, saving time and costs, and improving reliability	Gel filling must be chemically cleaned — messy, costly and time consuming
No stiff strength member needed, more flexible cable — easier to handle	Requires stiff cable strength member — more difficult to handle and install
Cable is "tight bound" and can be pulled around multiple bends or hung vertically (no fiber axial migration)	Should not be pulled around multiple bends or hung vertically (fiber axial migration) — installation limitations
Easy to terminate, no breakout kits or splicing required	Difficult to terminate, breakout kits or splicing required — time consuming, requires expensive equipment and skills
Lower total installed costs	Cable purchase cost may be slightly lower

SLOTTED RIBBON FIBER CABLES

- All of the fibers are laid out in rows, usually with 12 fibers per row, and then stacked on top of each other in this cable.
- Outside plant wire has been filled with gel to keep the water out.

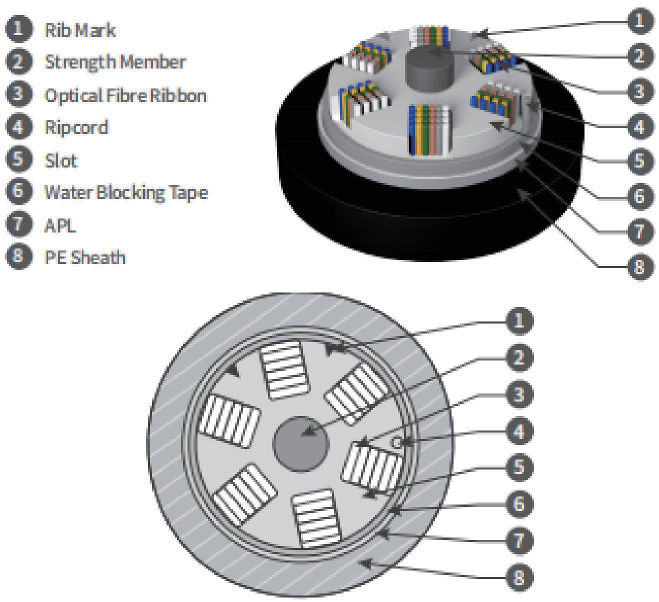


Figure 2.12: Slotted ribbon cable structure

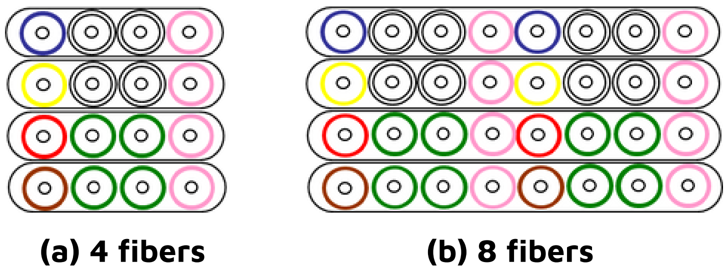


Figure 2.13: Slotted ribbon size
(a) 4 fibers (b) 8 fibers

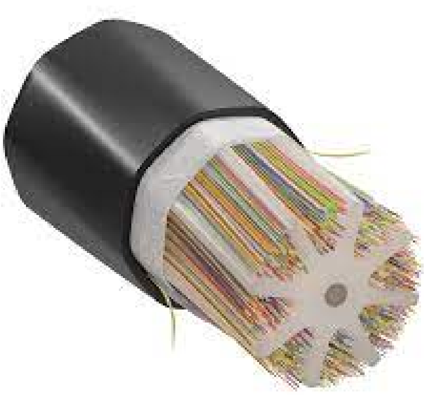


Figure 2.14: Slotted ribbon fiber cable

ARMORED CABLES

- It is common practise to use metal armoring between two jackets on cable buried directly in the ground in rodent-infested locations.
- The cable itself is made of conductive material.
- Proper grounding is essential.

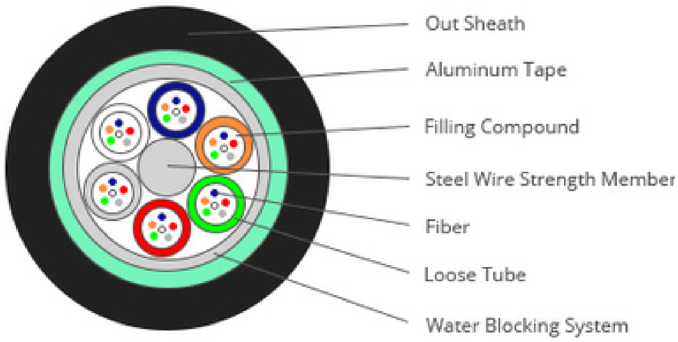


Figure 2.15: Armored cable structure

Figure 2.16: Armored fiber cable

FIBER OPTIC CABLES

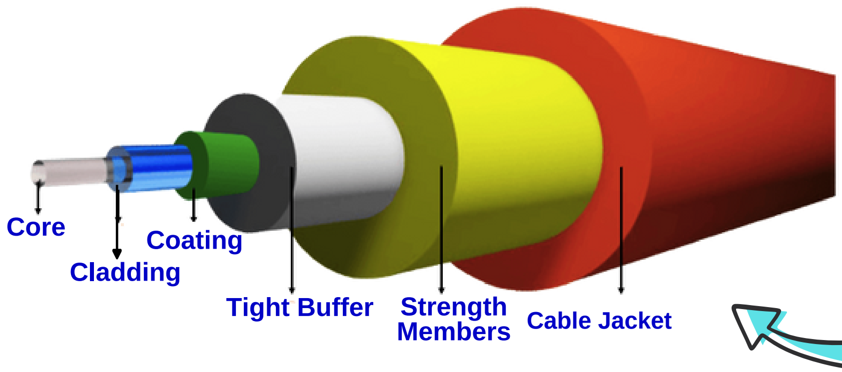
POINT 1: TRANSMISSION LOSSESS

- Dispersion
  - Intrinsic
  - Extrinsic
- Absorption losses
- Material scattering losses
  - Modal dispersion
  - Polarization Mode Dispersion (PMD) data network
  - Chromatic dispersion / material dispersion

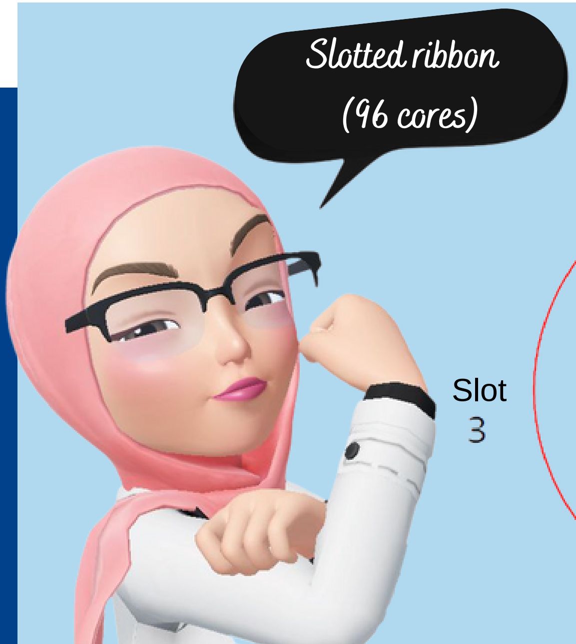
POINT 2: MODES & INDEX PROFILE

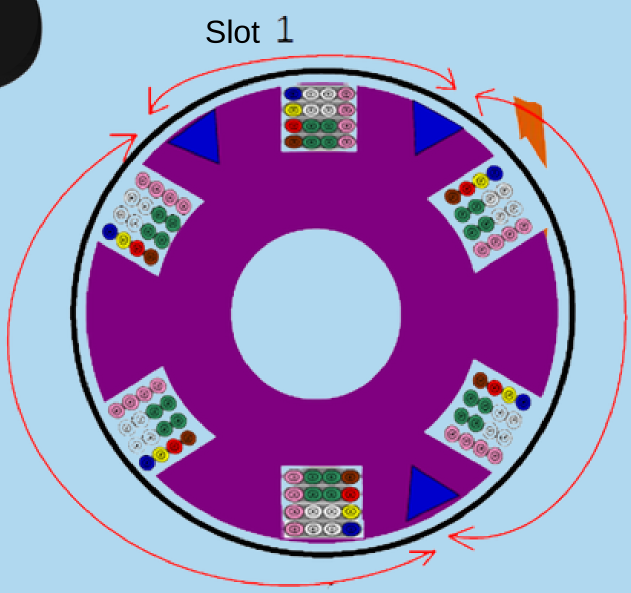
- Single Mode
- Multi Mode
  - Step Index
  - Graded Index

POINT 3: FIBER CABLE STRUCTURE

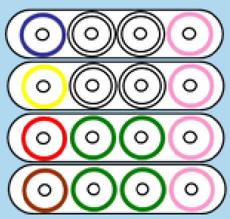


DID YOU KNOW?





Slotted ribbon color indicator for 4 fibers



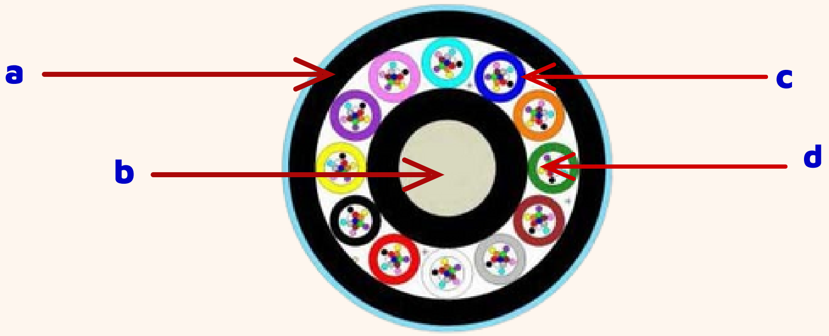
EXERCISES

EXERCISE 2.1:

How many fiber optic cores in one tube for a Loose Buffer Tube cable?

EXERCISE 2.2:

Name the cross-sectional parts of the fiber optic cable marked in the diagram below.



EXERCISE 2.3:

What will happen if the fiber cable is bend?

EXERCISE 2.4:

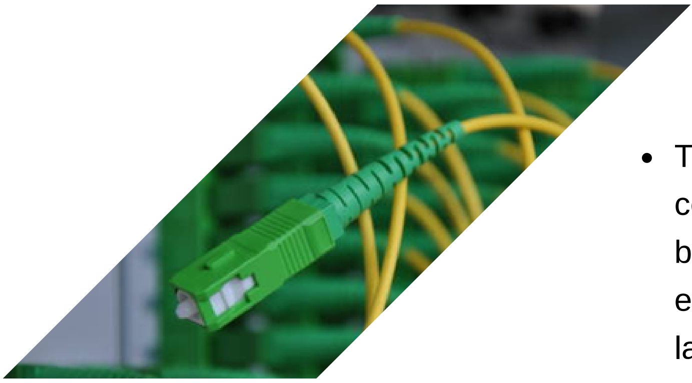
Single Mode, Multimode Graded Index, and Multimode Step Index are the three distinct kinds of fiber optic cables. Show how light travels via each of the fiber optic cables.

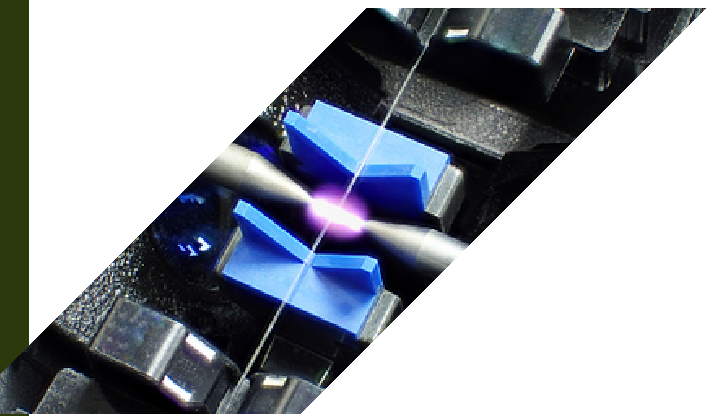
EXERCISE 2.5:

Give FIVE difference between intrinsic and extrinsic absorption losses.

EXERCISE 2.6:

Why does dispersion loss occur in optical fibers? Give an explanation based on the diagram.





INTRODUCTION

- The light sources and receiver utilised in optical communications. The sources are much smaller, but they also range from simple, low-cost light-emitting diodes (LEDs) to expensive, high-power laser diodes with sophisticated semiconductor architectures.

- In addition, it's critical to understand the source's properties in order to select the transmitter correctly.

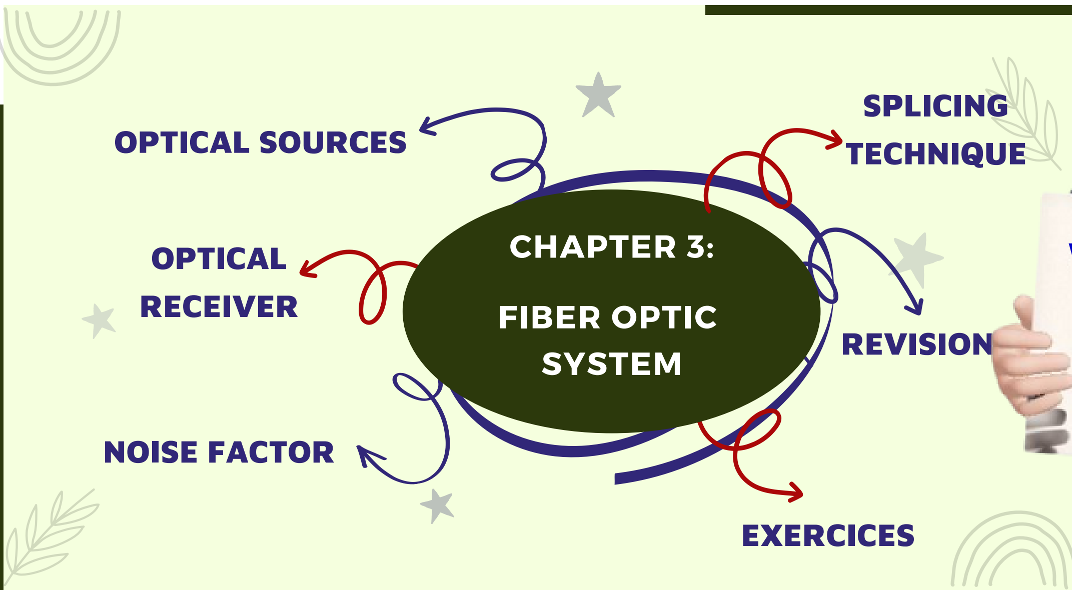
- The properties of LED and laser diode light sources are thus presented first in this chapter.

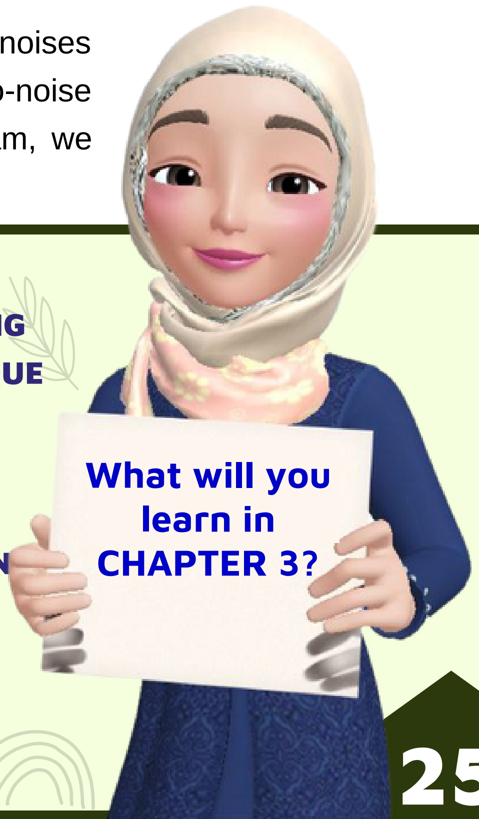
- A receiver must be present at the other end of an optical transmission connection.

- This device's function is to interpret the data contained in the optical signal. A photodetector and numerous electrical components make up an optical receiver.

- These electronics can range from a few basic amplification functions for reasonably strong, clear signals to hordes of complicated circuitry if the receiver has to understand weak, distorted signals at fast data rates.

- Then, by taking into account elements like the random noises connected to the photodetection process, the idea of signal-to-noise ratio, and the likelihood of mistakes happening in a data stream, we examine how these devices are employed in receivers.





OPTICAL SOURCES

- Electrical input signal is converted into a comparable optical signal by an optical transmitter.
- After that, the optical signal is launched into the cable.
- The main element of an optical transmitter is an optical source.
- Laser Diodes (LD) and Light Emitting Diode (LED) are common types of optical transmitters.

CHARACTERISTICS OF A COMMUNICATION LIGHT SOURCE:

The following characteristics are necessary for a light source in order to be beneficial in an optical link:

- The light source must be able to run continuously for several years at a variety of temperatures.
- A wide range of modulating frequencies must be able to be used to modulate the light output. The output wavelength for fiber links should fall inside one of the transmission windows for the chosen fiber type.
- The emission area needs to be small in order to couple a significant quantity of power into an optical fiber.
- In an optical fiber link, the output spectrum should be narrow to minimize material dispersion.
- Its operation must use a minimal amount of power.
- Modern solid state electronics must be able to use the light source.
- The device's input current must be changed in order to directly adjust the optical output power.
- Improved linearity to reduce intermodulation distortion and harmonics.
- Excellent coupling performance.
- A powerful optical output.
- Very dependable.
- Low cost and weight.

DID YOU KNOW?

These following **characteristics of LEDs**

1. Low Cost
2. Low Power
3. Relatively Wide Spectrum Produced
4. Incoherent Light
5. Digital Modulation
6. Analogue Modulation

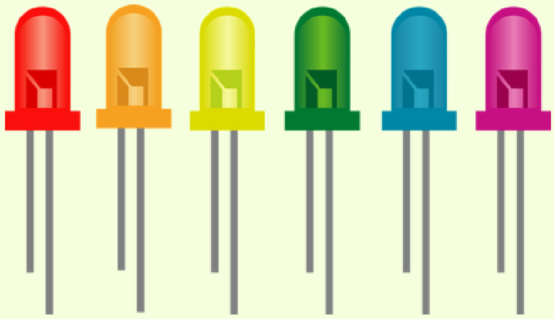


Figure 3.1:LED structure

LIGHT PRODUCTION

- In the transmission process, there is only one method that light may be produced, and that is by an electron rapidly transitioning from one (more stable) state of relatively high energy to another state of lower energy.
- When this occurs, the energy must go somewhere, and it frequently emits light.
- Naturally, this always occurs in relation to a specific material and structure.
- The involved electron can be relatively free within the substance or it might be loosely attached inside a molecule.
- A photon's ability to emit light can either occur naturally or be "stimulated" by the presence of another photon with the appropriate energy level.

SPONTANEOUS EMISSION

The typical case involves spontaneous emission. When an electron is raised to a high energy level, this condition is typically unstable, and the electron will soon (within a few picoseconds) return to a more stable state on its own, producing a photon in the process. While the wavelength of light released spontaneously will depend on how much energy the releasing electron needs release, the direction and phase will be arbitrary.

STIMULATED EMISSION

The operation of a laser is characterised by stimulated emission. An electron can sometimes remain in a high energy (excited) state for a considerable amount of time (a few microseconds) before changing states on its own. An electron can be "stimulated" by the presence of a photon of light to release its energy in the form of another photon while it is in this semi-stable (metastable) high energy state. In this scenario, the incident photon's energy (wavelength) must be within very strict limits.

It is essential to comprehend that when stimulated emission occurs, the emitted photon has the exact same wavelength, phase, and direction as the photon that stimulated it.

DID YOU KNOW?

The important **features of communication lasers** are as follows:

1. Spectral Width
2. Linewidth
3. Coherence Length and Coherence Time
4. Power
5. Operating Wavelength
6. Frequency Stability
7. Switching Time and Modulation
8. Tuning Range and Speed

LIGHT EMITTING DIODE (LED)

- An LED is a junction diode built of the semiconductor material gallium arsenide phosphide.
- LEDs used as optical fiber transmitters emit infrared radiation at 850 nm (0.85 m) wavelength.
- An LED is a two-lead semiconductor light source that emits light in response to an electrical current.
- It is a p-n junction diode, and when it is turned on, it produces light.
- When the leads receive an appropriate voltage.
- One of the best optoelectronic devices out there is the light emitting diode, or LED.

OPERATION

- LEDs are a relatively affordable and practical source of light.
- As a result of their low output intensity, LEDs are widely utilized with multimode fibres.
- In low data rate digital transmission systems that operate at speeds of up to 30 Mbps, spreading of output pulses due to dispersion is not a major concern.
- When a current is passed through a Light-Emitting Diode (LED), a semiconductor device (using a p-n junction diode), it spontaneously generates incoherent light.
- GaAs and AlGaAs are frequently used to produce LEDs for the 850-nm area.
- Utilizing InGaAsP and InP, LEDs for the 1330 nm and 1550 nm wavelength ranges are created.
- LEDs produce light through spontaneous emission, or the recombination of electrons and holes.

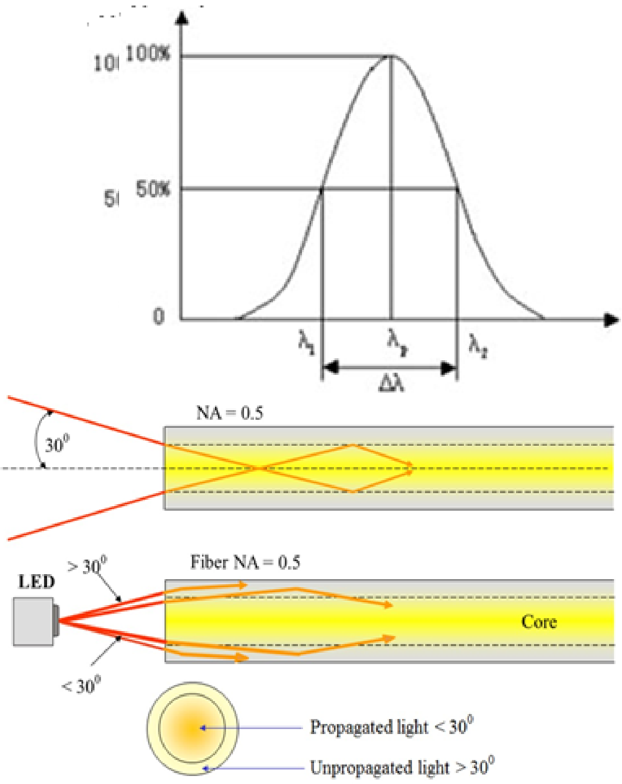


Figure 3.2: Peak Wavelength & Spectral Width of LED

DID YOU KNOW?

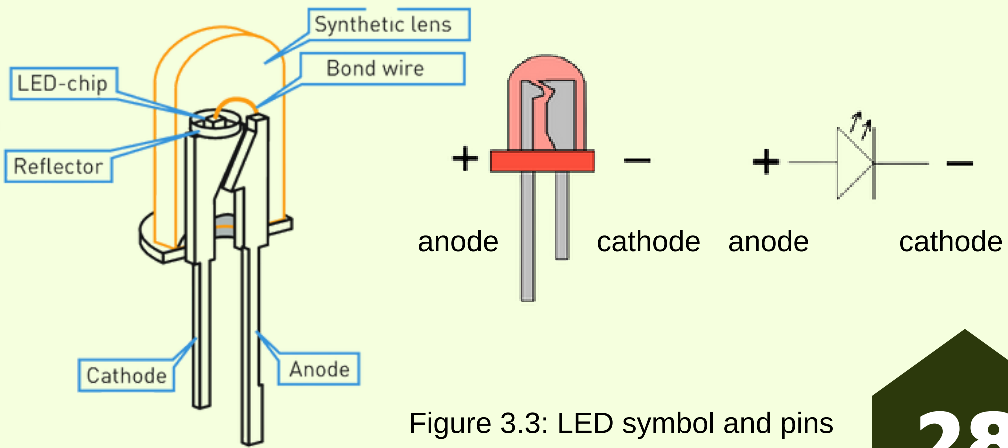


Figure 3.3: LED symbol and pins

INJECTION LASER DIODE (ILD)

- "Light Amplification by Stimulated Emission of Radiation" is the definition of a laser.
- Through stimulated emission, a laser generates coherent light.
- It can be used in optical transmitters for telecommunications and data communications.
- Since it emits light coherently, a laser can be concentrated to a small area thanks to spatial coherence.
- A coherent, narrowly concentrated beam of photons is a laser.

OPERATION

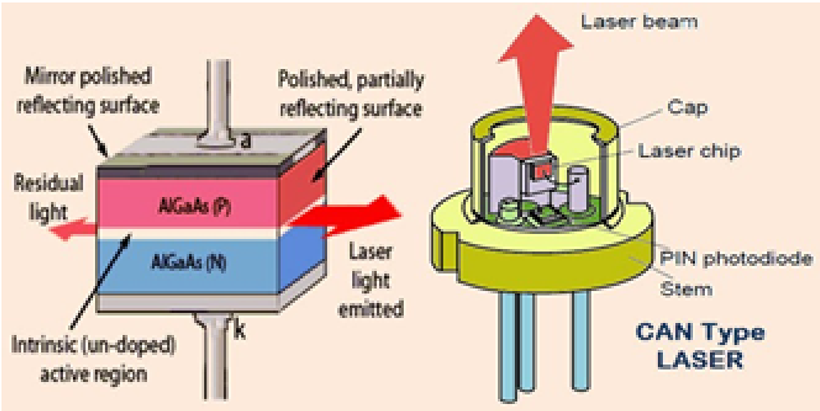


Figure 3.4: Laser diode structure

- Light Amplification by ‘Stimulated Emission’ and Radiation (LASER).
- Coherent light (stimulated emission).
- Narrow beam width (very focused beam).
- High output power (amplification).
- Narrow line width because only a small number of wavelengths will generate positive feedback and amplify (optical filtering).
- Due to the fact that lasers generate coherent light, they have an extremely small spectral bandwidth. The lasers can transport data at significantly greater rates as a result of their small spectral breadth.

DID YOU KNOW?

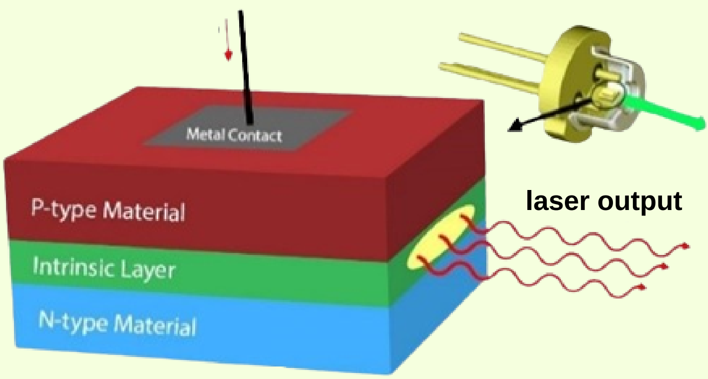


Figure 3.5: Laser diode construction

OPTICAL RECEIVER

- The ionisation of a semiconductor material is the basis for the majority of light detectors used in communications systems.
- Although there are many various types of devices, they can all be seen as variations on a single fundamental concept rather than as devices involving fundamentally dissimilar principles.

There are four crucial factors to consider when talking about photodetectors:

1 Responsivity of the Detector

This is the proportion of optical power input to output current. Thus, this is the device's effectiveness.

2 Range of Spectral Response

This is the spectrum of wavelengths that the device will work in.

3 Response Time

This gauges how quickly the detector can react to changes in the intensity of the light coming in.

4 Characteristics of Noise

The device's ability to function at low input light levels depends on how much noise it produces

DID YOU KNOW?

2 types of photo diodes as optical detectors

- *Positive-intrinsic-negative (PIN) Photo Diode*
- *Avalanche photo diodes (APD)*

PIN PHOTODIODE

- A P-type and an N-type region are sandwiched by an inherent (very lightly doped) semiconductor region in a PIN photodiode.
- The fundamental concept underlying a structure based (PIN) is P-region, I-intrinsic, N-region
- When a photon strikes a semiconductor photodetector device and has more energy than the device's band gap, the photon's extra energy is absorbed by the band gap, causing an electron-hole pair to form across the band gap.

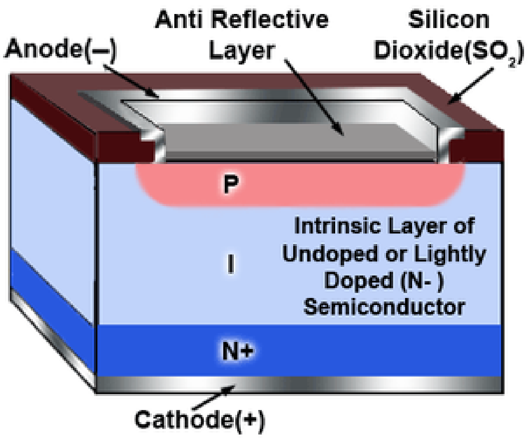


Figure 3.6: PIN photodiode construction

AVALANCHE PHOTO DIODE

- The main distinction between avalanche photodetectors (APD) and PIN diodes is that the APD device has a high intensity electric field area added to it.
- The incident photons in this region cause the main electron-hole pairs to form, and these electron-hole pairs are able to absorb enough kinetic energy from the strong electric field to collide with the atoms in this region, producing further electron-hole pairs.
- The avalanche effect is the method by which ionization produces many electron-hole pairs from a single incoming photon.

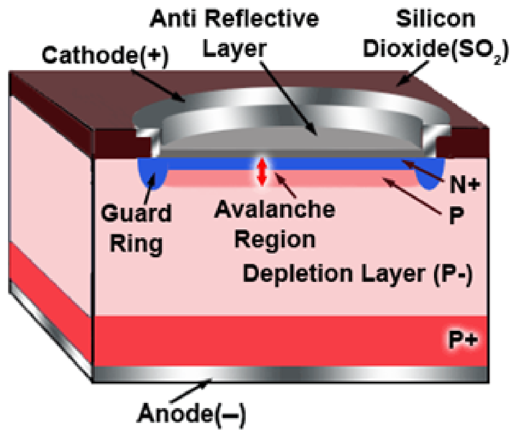


Figure 3.7: Avalanche photodiode construction

DID YOU KNOW?

PIN DIODE

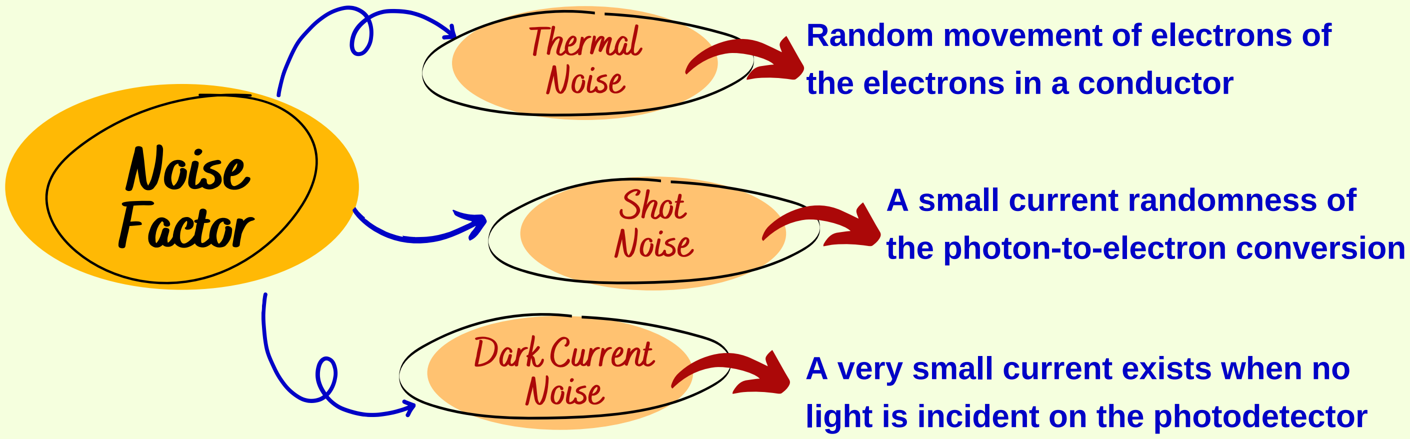
- The most common technique for transforming the incoming light into an electrical signal is a PIN diode.
- Their appearance is quite similar to that of lasers and LEDs.
- They can be terminated using a pigtail or other connectors, including ST, SC, and others.
- It makes use of either germanium or silicon as a semiconductor material.

AVALANCHE DIODE (APD)

- An avalanche diode can produce higher output signals.
- It has the benefits of a wide dynamic range, or the ability to handle both high and low light levels, and a good output at low light levels.
- Its disadvantages include increased noise levels, higher prices, the need for higher working voltages, and a gain that diminishes with temperature.

NOISE FACTOR IN THE OPTICAL RECEIVER

- Noise is defined as undesirable signal components that have a tendency to interfere with the signal's processing and transmission in a physical system.
- The photodiode's noise is the most critical. The three most common categories are:



THERMAL NOISE

- Thermal noise, also known as Johnson noise or Nyquist noise, is the random thermal movement of the electrons in a conductor.
- The thermal noise current it in a resistor, R may be expressed by its mean square:

$$i_t = \sqrt{\frac{4KTB}{R}}$$

$$K = 1.38x10^{-23}$$

K: Boltzmann's constant
T : Temperature (in Kelvin)
B: Post- detection (electrical) bandwidth of the system

SHOT NOISE

- Shot noise is a small current that results from the random conversion of photons to electrons.
- Any photocurrent produced, whether dark noise or not, will have a shot noise mechanism attached to it.
- Avalanche photodiodes have higher shot noise than other devices due to the multiplication factor.

$$i_q = \sqrt{2qIB}$$

$$q = 1.602x10^{-19}$$

DARK CURRENT NOISE

- A very small current known as "dark current" exists when no light is incident on a photodetector.
- This reverse current results from bulk leakage and surface recombination of thermally stimulated electrons in the depletion region.
- This dark current noise gets greater as the temperature and voltage are increased.

$$i_d = \sqrt{2qI_dB}$$

$$q = 1.602x10^{-19}$$

I_d is a dark current

EXAMPLE 3.1:

At 275K temperature, a Silicon PIN photodiode operates at 15GHz. The load resistance is 100k and the current is 100A, whereas the dark current is 0.3nA. Determine the photodiode's thermal noise and shot noise.

SOLUTION:

Thermal Noise, i_t

$$i_t = \sqrt{\frac{4KT\Delta f}{R}}$$

$$= \sqrt{\frac{4(1.38 \text{ x } 10^{-23})(275)(15 \text{ x } 10^9)}{100 \text{ x } 10^3}}$$

$$\underline{= \mathbf{4.77 \text{ x } 10^{-8} \text{ atau } 0.477 \text{ nA}}}$$

Shot Noise, i_s

$$i_s = \sqrt{2qI\Delta f}$$

$$= \sqrt{2(1.602 \text{ x } 10^{-19})(100 \text{ x } 10^{-6})(15 \text{ x } 10^9)}$$

$$\underline{\mathbf{= 6.92 \text{ x } 10^{-7} \text{ atau } 0.069 \text{ nA}}}$$

Dark Current Noise, i_d

$$i_d = \sqrt{2qI_d\Delta f}$$

$$= \sqrt{2(1.602 \text{ x } 10^{-19})(0.3 \text{ x } 10^{-9})(15 \text{ x } 10^9)}$$

$$\underline{\mathbf{= 6.92 \text{ x } 10^{-7} \text{ atau } 0.069 \text{ nA}}}$$

SIGNAL-TO-NOISE RATIO (SNR)

- The ratio of the total signal to the total noise indicates how much greater the signal is than the noise.
- It determines the quality of the signal.
- At the output of an optical receiver, the signal-to-noise ratio, also known as SNR or S/N, is calculated as the difference between the signal power and the noise power and shown as follows:

$$SNR = \frac{Signal\ Power\ (S)}{Noise\ Power\ (N)} = \frac{i_{signal}^2 R_L}{i_{noise}^2 R_L}$$

$$SNR = 10log\frac{S}{N}$$

RECEIVER SENSITIVITY

- The signal that meets a specified SNR value is known as receiver sensitivity
- While the smallest detectable signal corresponds to a receiver sensitivity of 1, which offers SNR = 1, a higher value of SNR is sometimes provided to assure a specific amount of precision.
- In a digital system, the lowest optical energy or corresponding mean number of photons per bit needed to achieve a certain BER is known as the receiver sensitivity.

RESPONSIVITY

- A detector system's responsiveness is a measurement of its input-output gain.
- Responsivity evaluates the ability of a photodetector, specifically, to detect electrical output divided by optical input.
- A photodetector's responsiveness is often indicated in either volts or amps for each watt of incident radiant energy.

SPECTRAL RESPONSE

- The relative effectiveness of detecting light or another signal in relation to the frequency or wavelength of the signal is known as the spectral response.
- A photoconductor's capacity to react to incident light of various wavelengths is known as photo response.
- Therefore, the spectral response of the detector should coincide with the spectral curve of the optical source.

RESPONSE TIME

Two factors influence the response time:

1. **Drift** of the photogenerated electrons and holes in the depletion layer.
2. **Diffusion** of the photogenerated electrons and holes in the diffusion zones.

APPLY SPLICING TECHNIQUE

- A fiber optic splice is a low-loss link that joins two fibers permanently or temporarily.
- Both mechanical splicing and fusion splicing can be used to create such a link.
- The majority of splices are permanent and are frequently utilized to build lengthy optical linkages.
- Temporary splices are used for urgent cable repairs, testing while installing, and troubleshooting.
- When fiber optic bonding is carried out correctly and with high-quality tools, the total splice loss for mechanical and fusion splices, respectively, ranges from 0.05 to 0.10 dB.

ARC FUSION SPLICING

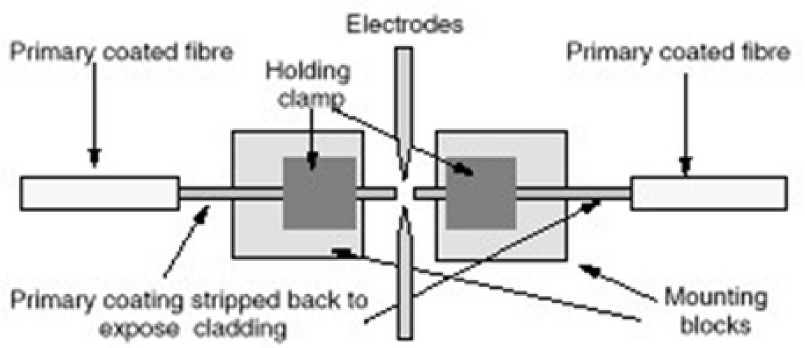


Figure 3.8: Arc fusion splicing

Arc Fusion Splicing Technique

https://www.youtube.com/watch?v=xba2MThR9Ls

- In fusion splicing, an electric arc actually welds (fuses) two strands together.
- Performed using a robotic device called a fusion splicer:
  i. Aligns the two fiber ends mechanically
  ii. The fiber tips are fused together by passing a spark across them.
- Fusion splicing, which offers the lowest insertion loss and almost no back reflection, is the most popular splicing technique.

MECHANICAL SPLICING

- To connect two strands end to end, mechanical splicing is used.
- When two fiber ends are joined mechanically, they can be clamped inside a structure or joined using glue.
- Include index-matching gels and transparent adhesives.
- Transparent adhesives are epoxy resins that allow index matching between the joined fibers as well as mechanical splice sealing.

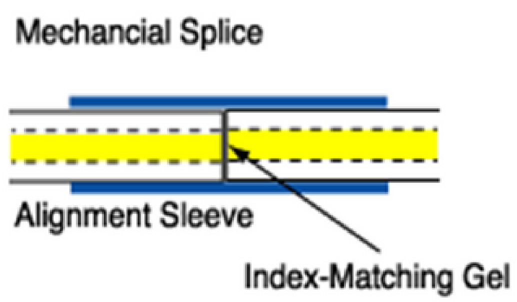
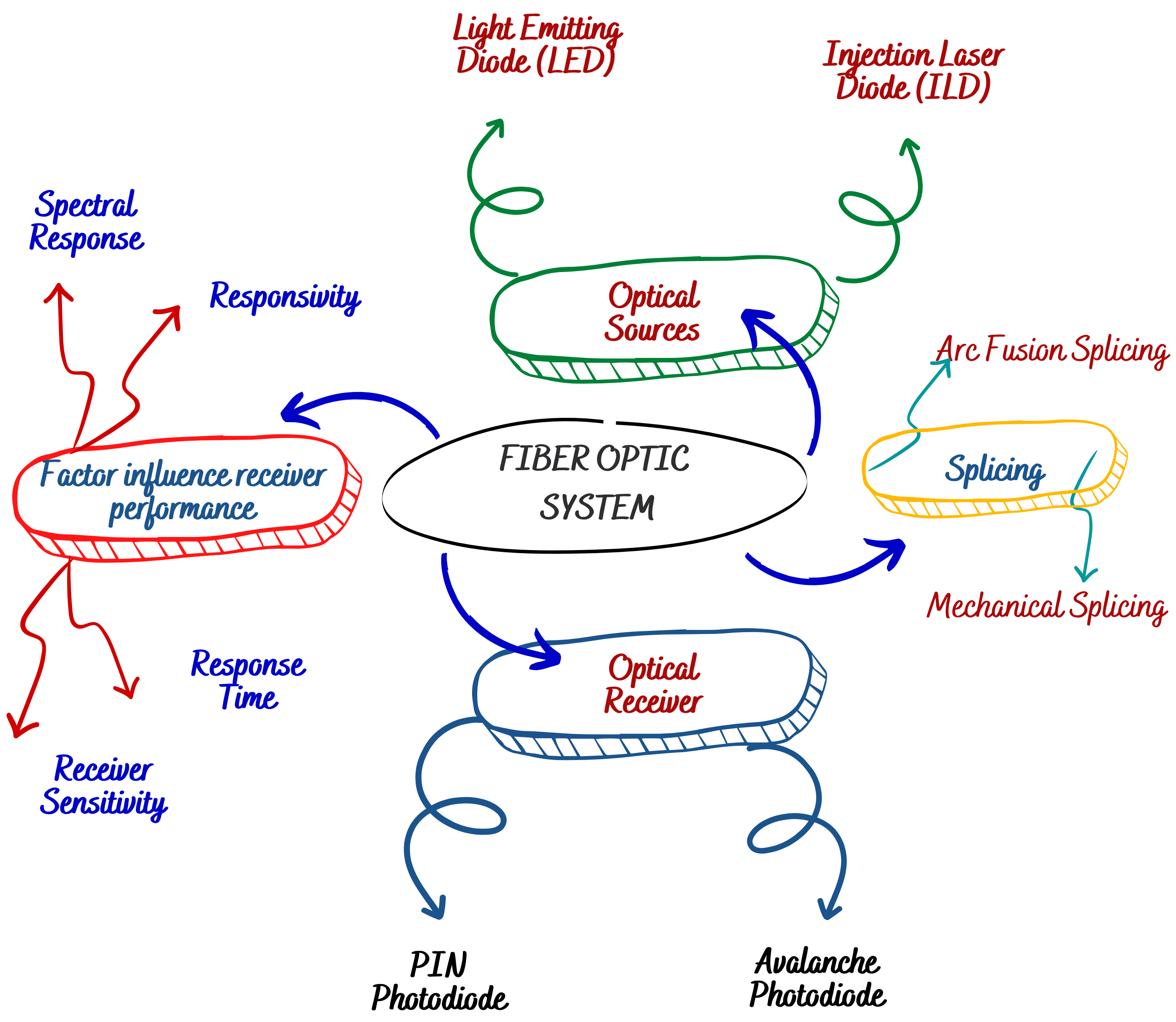


Figure 3.9: Mechanical splicing



IMPORTANT FORMULA

THERMAL NOISE

$$i_t = \sqrt{\frac{4KTB}{R}}$$

$$K = 1.38x10^{-23}$$

SHOT NOISE

$$i_q = \sqrt{2qIB}$$

$$q = 1.602x10^{-19}$$

DARK CURRENT NOISE

$$i_d = \sqrt{2qI_dB}$$

$$q = 1.602x10^{-19}$$

I_d is a dark current

SIGNAL-TO-NOISE RATIO (SNR)

$$SNR = \frac{Signal\ Power\ (S)}{Noise\ Power\ (N)} = \frac{i_{signal}^2 R_L}{i_{noise}^2 R_L}$$

$$SNR = 10log\frac{S}{N}$$

EXERCISE 3.1:

A Si PIN photodiode has an active light receiving area of diameter 0.4mm. When the incident optical power at wavelength 700nm is 1.26x10-7W, it generates a photocurrent of 56.6nA. What is Responsivity of the photodiode at 700nm?

EXERCISE 3.2:

A photodiode incorporated into an optical fiber receiver working at a wavelength of 1.55um has a dark current of 500nA at the operating temperature. When the incident optical power at this wavelength is 1mW and the responsivity of the device is 0.6AW-1. Determine the photocurrent of an incident.

EXERCISE 3.3:

For an amplifier with an outputpower of 10W and an outputnoise power of 0.01W, determine the signal to noise power ratio.

EXERCISE 3.4:

Determine the noise voltage produced by a 1MΩ resistor at room temperature (17 degree celcius) over a 1MHz bandwidth.

EXERCISE 3.5:

A Si PIN photodiode is operating at 50GHz at 300K. The current is 200 µA, the dark current is 0.5 nA and the load resistance is 50 MΩ. Find the thermalnoise, shot noise, and total noise.

EXERCISE 3.6:

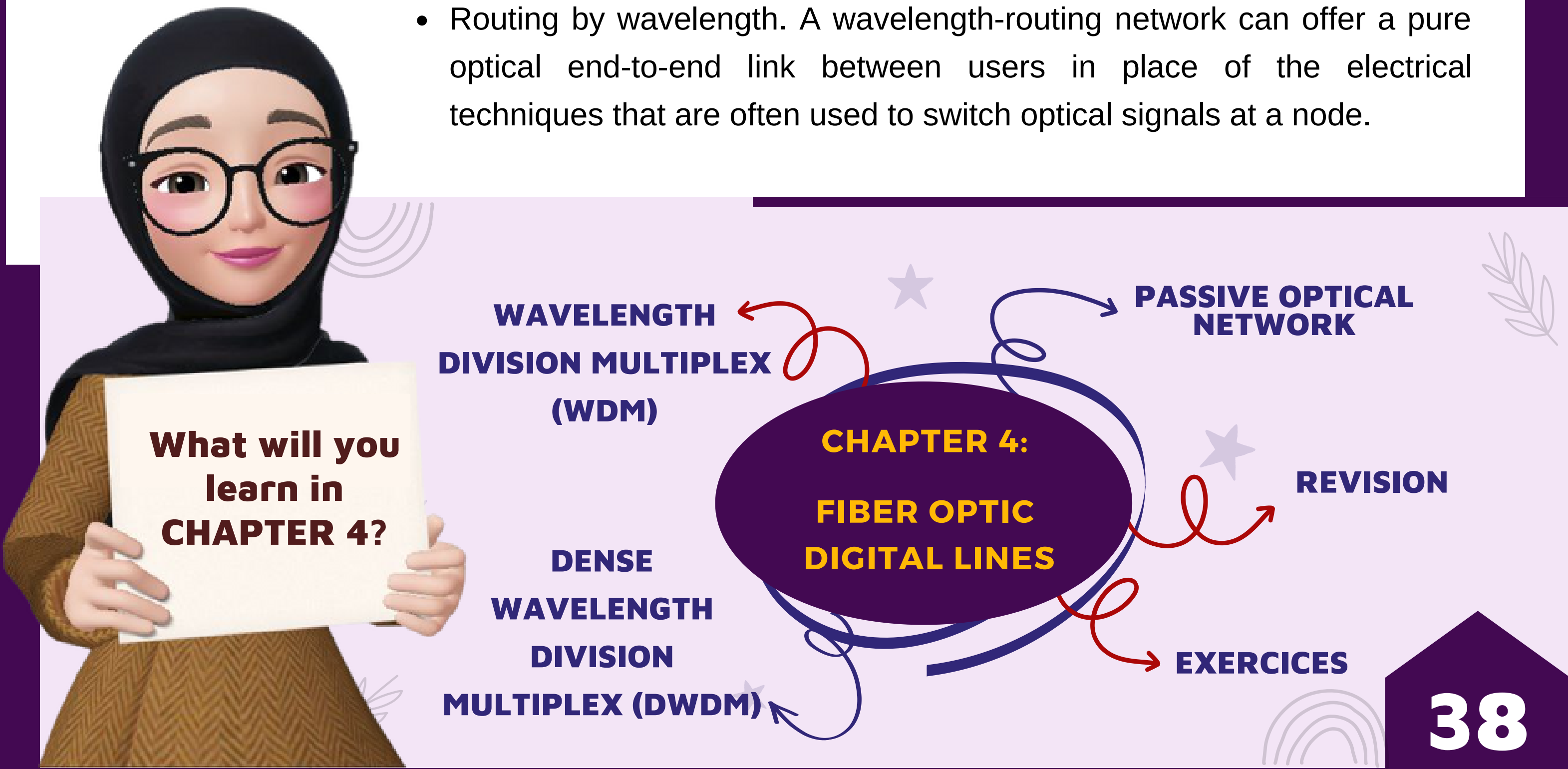
Find the Shot noise current for a diode with a forward bias of 1mAover a 100kHz.

EXERCISE 3.7:

For an amplifier with an output signal voltage of 4V, an output noise voltage of 0.005V and input and output resistance of 50Ω. Determine the SNR.

INTRODUCTION

- The ability to simultaneously transmit many wavelengths chosen from the spectral ranges spanning the O-band to the L-band through a single fiber is a key feature of optical communication links.
- Wavelength division multiplexing, or WDM, is a technique that combines many wavelengths onto a single fiber.
- The WDM technique and frequency division multiplexing (FDM) used in microwave radio and satellite systems are conceptually equivalent.
- The following are some of the primary WDM system features:
  - Capacity expansion. WDM has traditionally been used to increase the transmission capacity of point-to-point fiber optic networks.
  - The transparency. Each optical channel may contain any transmission format, which is a key feature of WDM. As a result, without the requirement for a common signal structure, rapid or slow asynchronous and synchronous digital data as well as analogue information can be conveyed simultaneously and independently over the same fiber by using multiple wavelengths.
  - Routing by wavelength. A wavelength-routing network can offer a pure optical end-to-end link between users in place of the electrical techniques that are often used to switch optical signals at a node.



- Technology that multiplexes many optical carrier signals onto a single optical fibre by utilising several wavelengths
- The optical equivalent of frequency-division multiplexing is called WDM.
- Light sources with separate signal modulations and various wavelengths of emission.
- An optical channel is a wavelength that is distinct from another.
- Light from the various sources is mixed and sent through a single optical fiber.
- The wavelengths are then re-separated or demultiplexed at the opposite end.

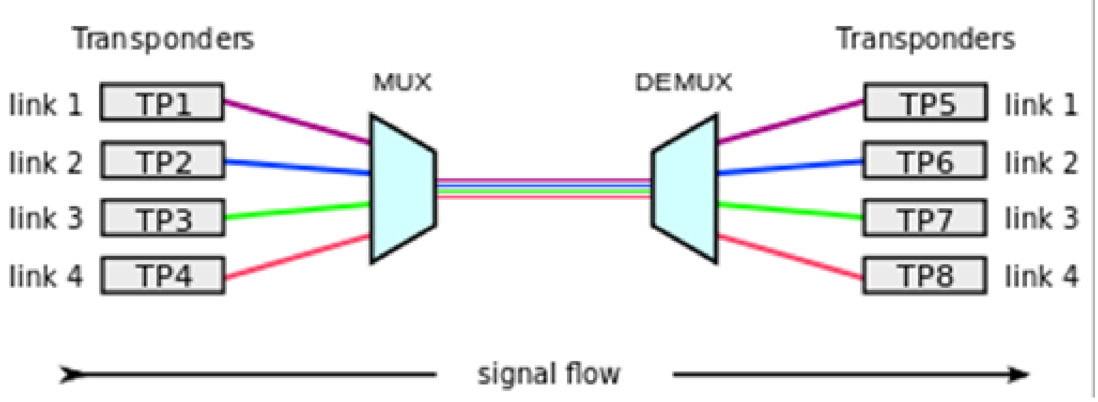


Figure 4.1: Wavelength division multiplexing system

CONCEPT OF WDM

- Broad channel spacing, several hundred nm.
- multiple channels of information carried over a single fibre, each using a different wavelength.
- A communicates with X and B with Y as though a dedicated fibre is being used for each signal.
- Typically, one channel uses 1310 nm and the other 1550 nm.
- WDM has been referred to as Coarse WDM or CWDM to distinguish it from DWDM

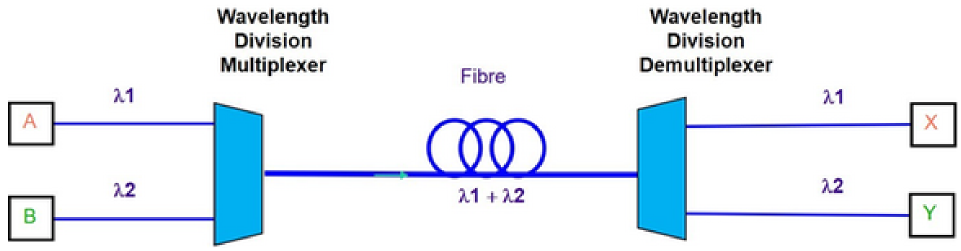
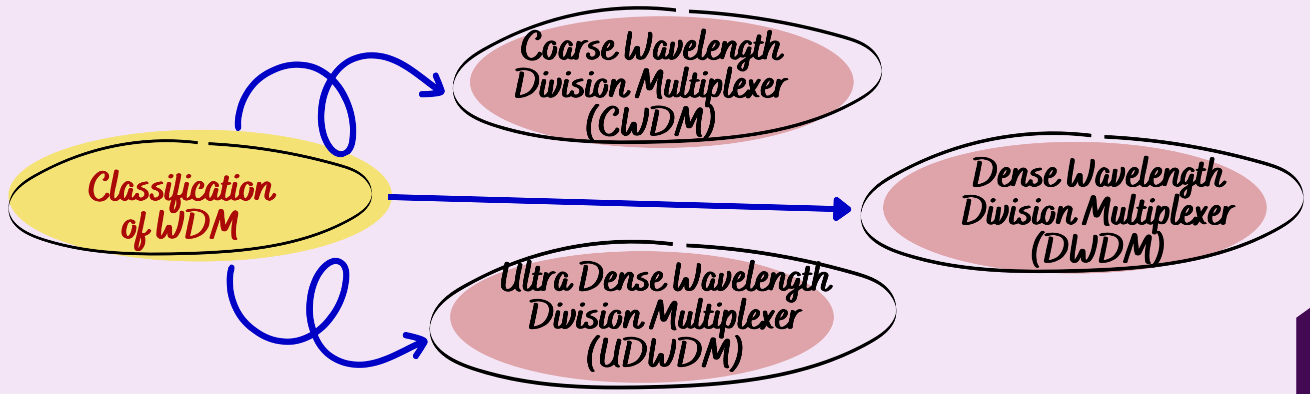


Figure 4.2: Concept of wavelength division multiplexing

DID YOU KNOW?



- A method of combining data from many sources onto an optical wire while simultaneously transmitting each information on a distinct light wavelength.
- DWDM allows for the multiplexing of up to 80 (and possibly more) various wavelengths or channels of data into a light stream that is sent via a single optical cable.

CONCEPT OF DWDM

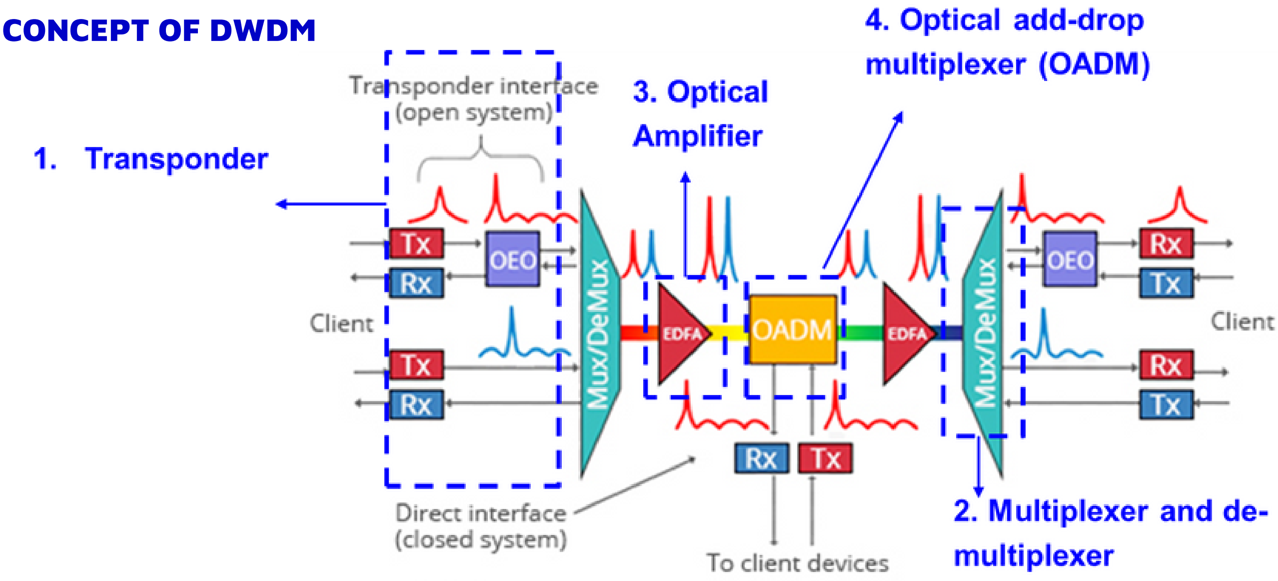


Figure 4.3: Concept of dense wavelength division multiplexing

TRANSPONDER

Transponders convert optical signals from one incoming wavelength to another outgoing wavelength suitable for DWDM applications.

OPTICAL AMPLIFIER

A weak signal enters the erbium-doped fiber, into which light at 980 nm or 1480 nm is injected using a pump laser to amplify the signal.

MULTIPLEXER & DE-MULTIPLEXER

- Multiplexer - contains a one wavelength converting transponder for each wavelength carried.
- De multiplexer - separates all of the individual wavelengths of the composite signal out to individual fibers.
- Two system in Mux / De Mux is Fiber Bragg Grating (FBG) and Multilayer Interference Filters.

OPTICAL ADD-DROP MULTIPLEXER (OADM)

An Optical Add-Drop Multiplexer allow access to individual DWDM signals without conversion back to an electronic domain.

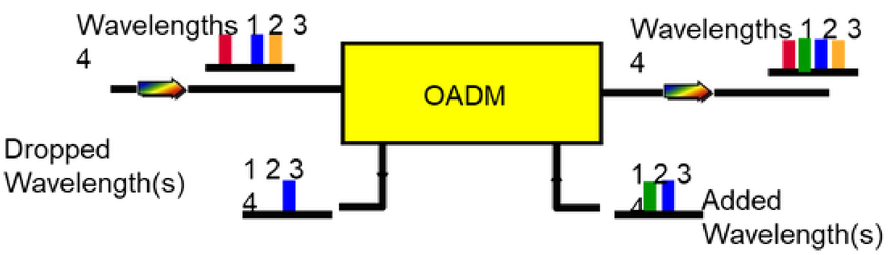


Figure 4.4: Concept of OADM

- Passive because there is no need for electrically powered active equipment between the central office (or hub) and the consumer location.
- a network where fibre optic cabling carries signals all the way to the end user (instead of copper).
- It is called passive because there isn't any active equipment that has to be powered by electricity between the hub or central office and the consumer location.
- The technology can be referred to as a FTTx network depending on where the PON finishes, which often enables a point-to-point or point-to-multipoint connection from the central office to the subscriber's residence.
- APON, BPON, GPON, EPON, WPOM, and CPON are examples of PON types.

FTTx Architechture

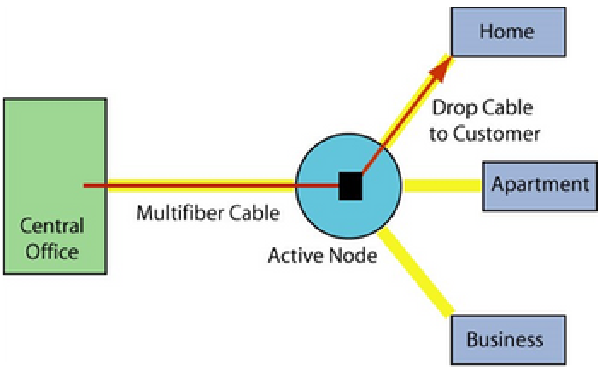


Figure 4.5: FTTx Architecture Active Star Network

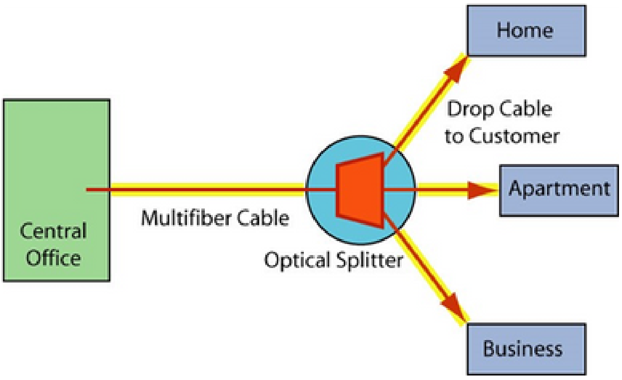
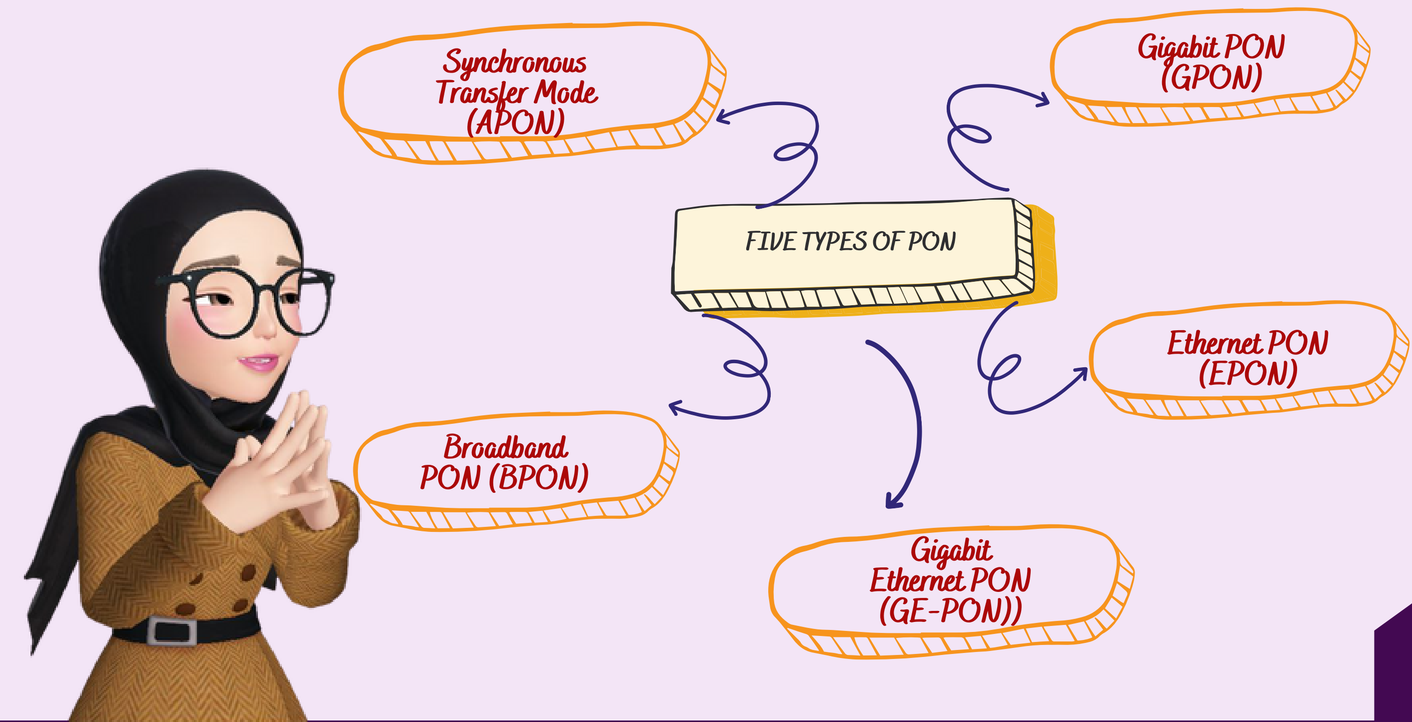


Figure 4.6: FTTx Architecture Passive Optical Network (PON)

DID YOU KNOW?



PASSIVE OPTICAL NETWORK COMPONENTS

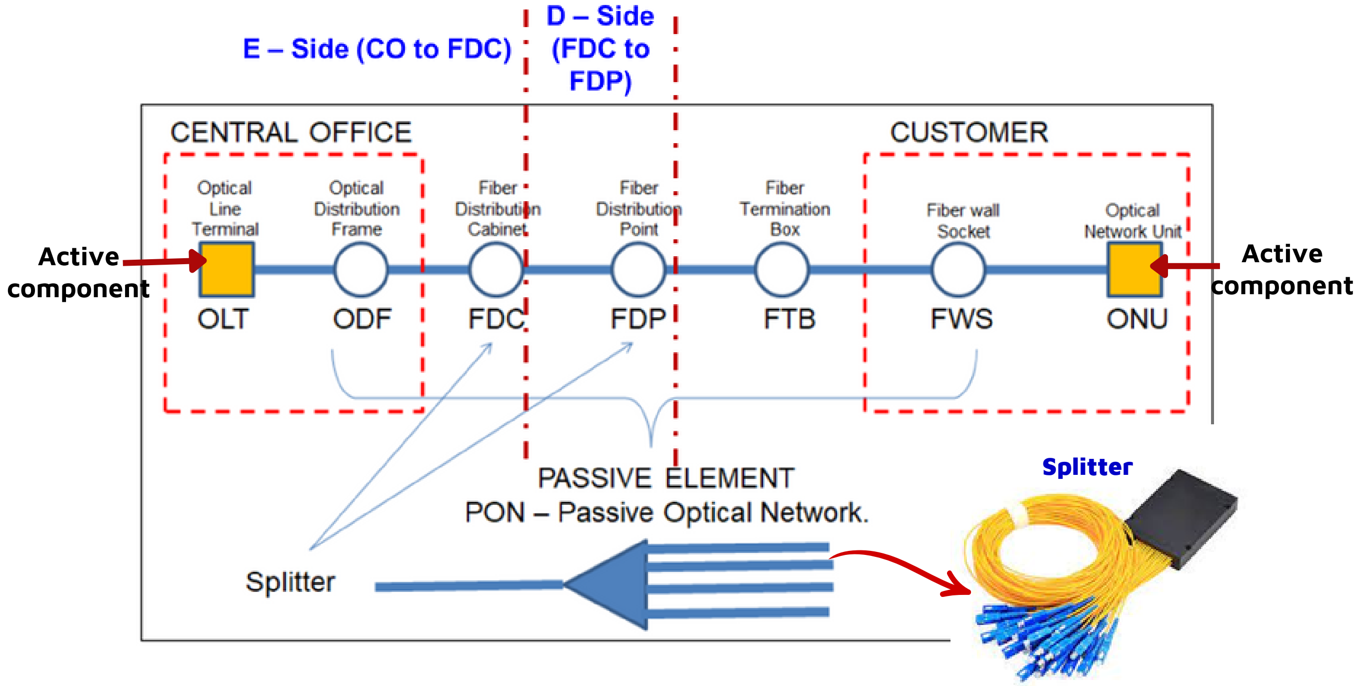


Figure 4.7: Passive Optical Network (PON) components

OPTICAL LINE TERMINAL (OLT):

The OLT serves as the interface between PON and the backbone network and is situated in the service provider's central office.

OPTICAL DISTRIBUTION FRAME (ODF):

Provides flexibility of the distribution of fiber in the CO and serves to connect the cable from the outside i.e. from the cabinet to the OLT.

FIBER DISTRIBUTION CABINET (FDC):

Part that connects main optic cable (E side) to external distribution cable (D side).

FIBER DISTRIBUTION POINT (FDP):

As a distribution part/point from distribution cable to 'drop fiber' at customer premises. Three type of FDP are FDP Pedestal, FDP Pole / Wall and FDP Closure.

FIBER TERMINATION BOX (FTB):

Installed/mounted at wall outside customer premises to connect between 'drop fiber' to internal fiber (inside customer premises). FTB must be installed on the wall of the customer's premises at least 1500mm from the floor (ground).

OPTICAL NETWORK UNIT (ONU):

The ONU offers the service interface to end users and is situated close to those consumers.

FIBER WALL SOCKET (FWS):

Part that connects internal fiber to 'bend insensitive fiber' inside customer premises and mounted around 30cm from floor.

SPLITTER:

Divides a single input to broadcast to several consumers, greatly reducing the cost of the lines. A bi-directional devices that allow communication in both directions.

PRINCIPAL PON ARCHITECTURE

- A passive splitter is used in a PON system to divide a single input and "broadcast" signals to several users downstream.
- The passive splitter serves as a combiner upstream to link every user to a single shared PON port.
- Signals from the house are sent back to the FTTH system at the central office using a low-cost laser.

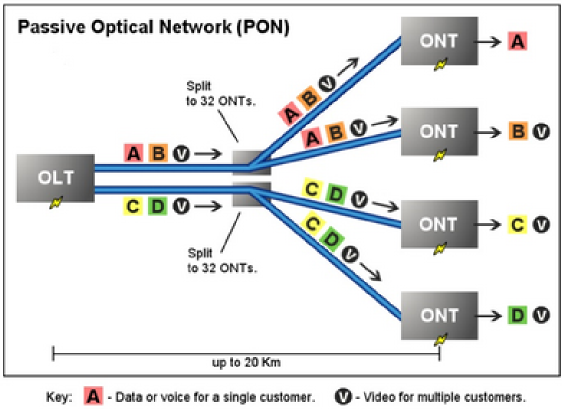


Figure 4.8: Architecture of PON

INVESTIGATE OF PON: FIBER TO THR LOOP (FTTL)

FTTP: FIBER-TO-THE-PREMISES

High-speed connection optical fiber that has been run into a subscriber's house from a central office is referred to by this general term. FTTH or FTTB fiber optic lines may be used as examples.

FTTC: FIBER-TO-THE- CURB/CABINET

Direct fiber connections from the central office to the outside shelters on curbs next to residential areas or any type of commercial setting.

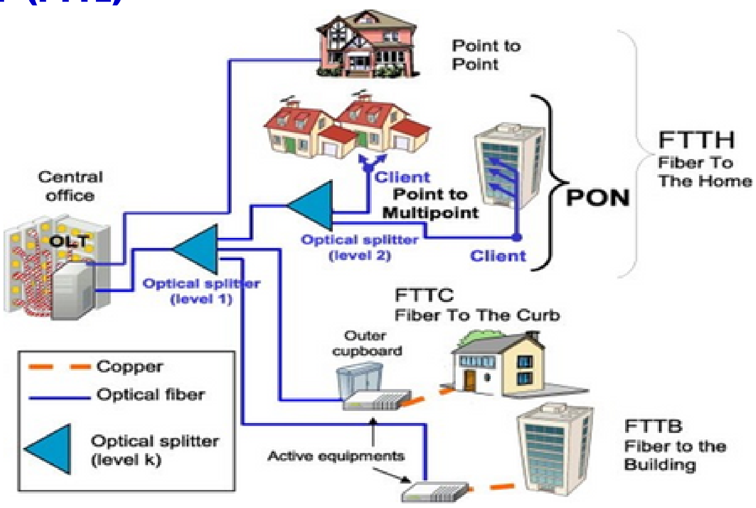


Figure 4.9: PON: Fiber to the loop(FTTL)

FTTH: FIBER-TO-THE-HOME

Fiber can be found at places where the living space ends, such a box on a house's exterior wall.

FTTB: FIBER-TO-THE- BUILDING

The final connection to each individual living area is done via various methods when fiber reaches the building's perimeter, such as the basement in a multi-dwelling unit.

DID YOU KNOW?

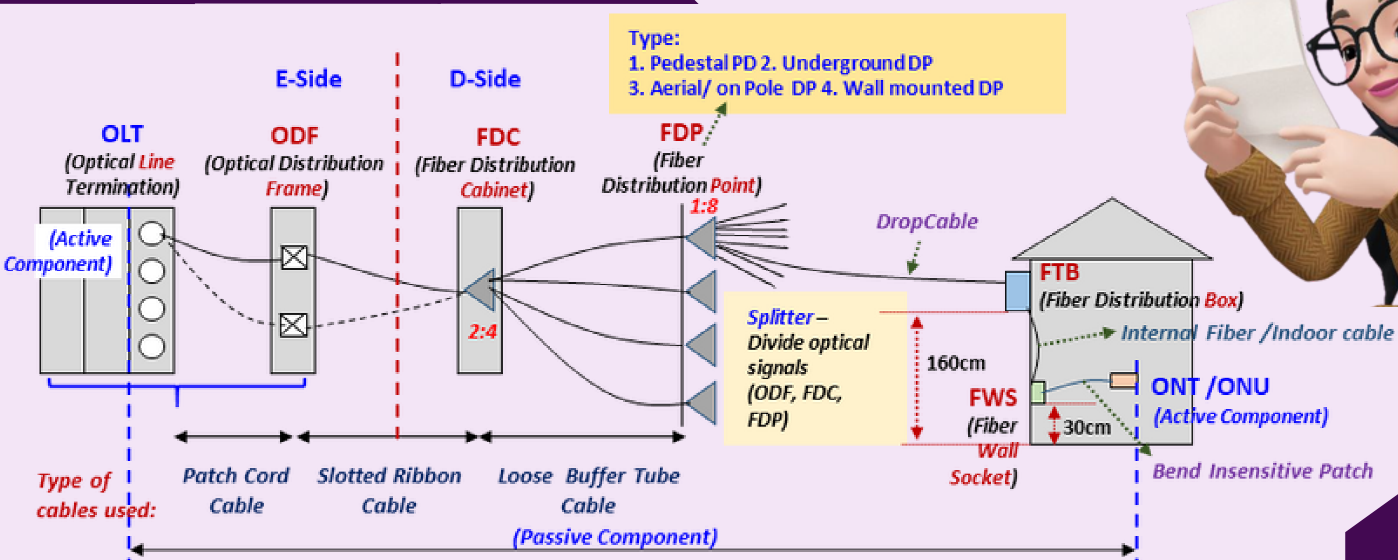
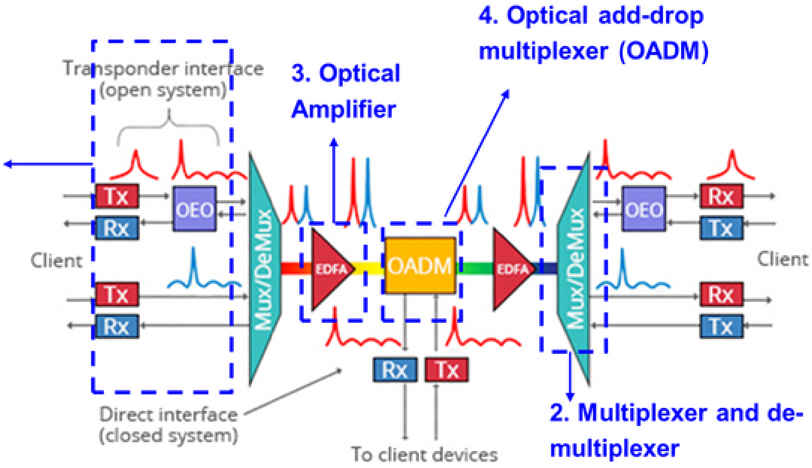


Figure 4.10: Structure components of PON

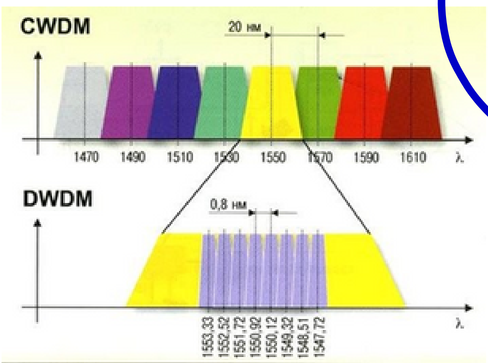
FIBER OPTIC DIGITAL LINE

Multiplexing Technique

- UDWDM
- CWDM
- DWDM

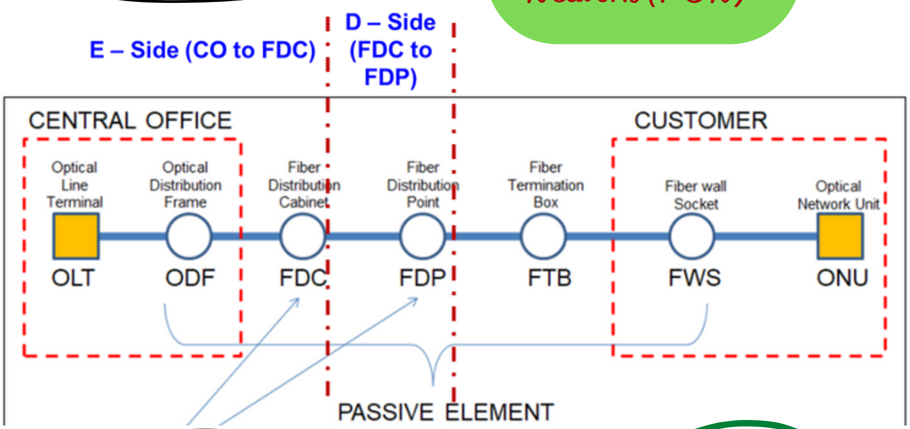


- Fiber Bragg Grating (FBG)
- Multilayer Interference Filters



Passive Optical Network (PON)

Main Component



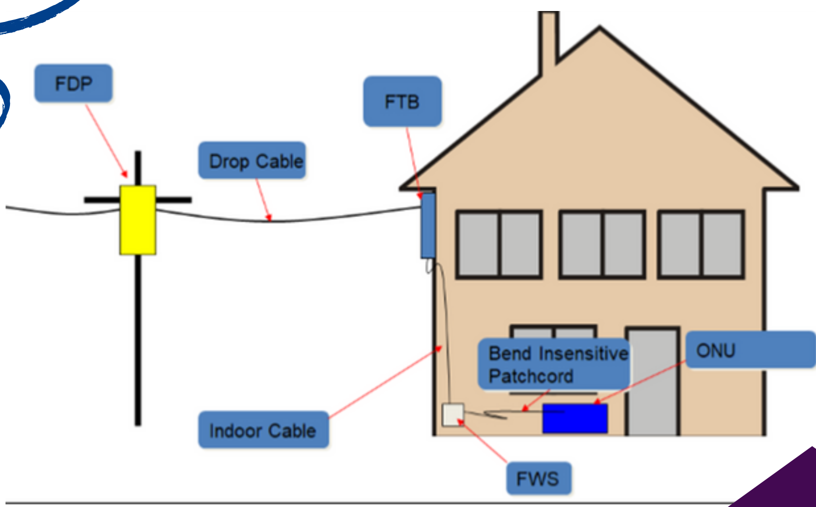
5 types of PON

- Synchronous Transfer Mode (APON)
- Broadband PON (BPON)
- Gigabit PON (GPON)
- Ethernet PON (EPON)
- Gigabit Ethernet PON (GE-PON))

Fiber In The Loop (FITL)

- FTTP
- FTTC
- FTTB
- FTTH

Installation of FTTH



EXERCISE 4.1:

List FOUR (4) classifications of Wavelength Division Multiplexing (WDM).

EXERCISE 4.2:

Fiber in the Loop (FITL) is an implementationsystem or upgrading portions of thepublic switched Telephone Network (PSTN) with optical fiber technology. Describe Fiber to the Home (FTTH), Fiber to the Building (FTTB) and Fiber to the Curb (FTTC).

EXERCISE 4.3:

A Passive Optical Network (PON) system utilizes passive splitter that takes one input and split it to ‘broadcast’ signals downstream to many users. Illustrate PON main components and basic PON architecture terminated with different types of Fiber in the Loop (FITL) application.

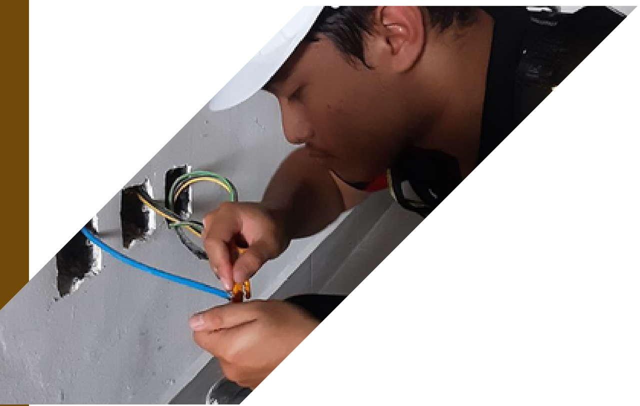
EXERCISE 4.4:

Identify FIVE (5) main components of Dense Wavelength Division Multiplexer (DWDM) system.

EXERCISE 4.5:

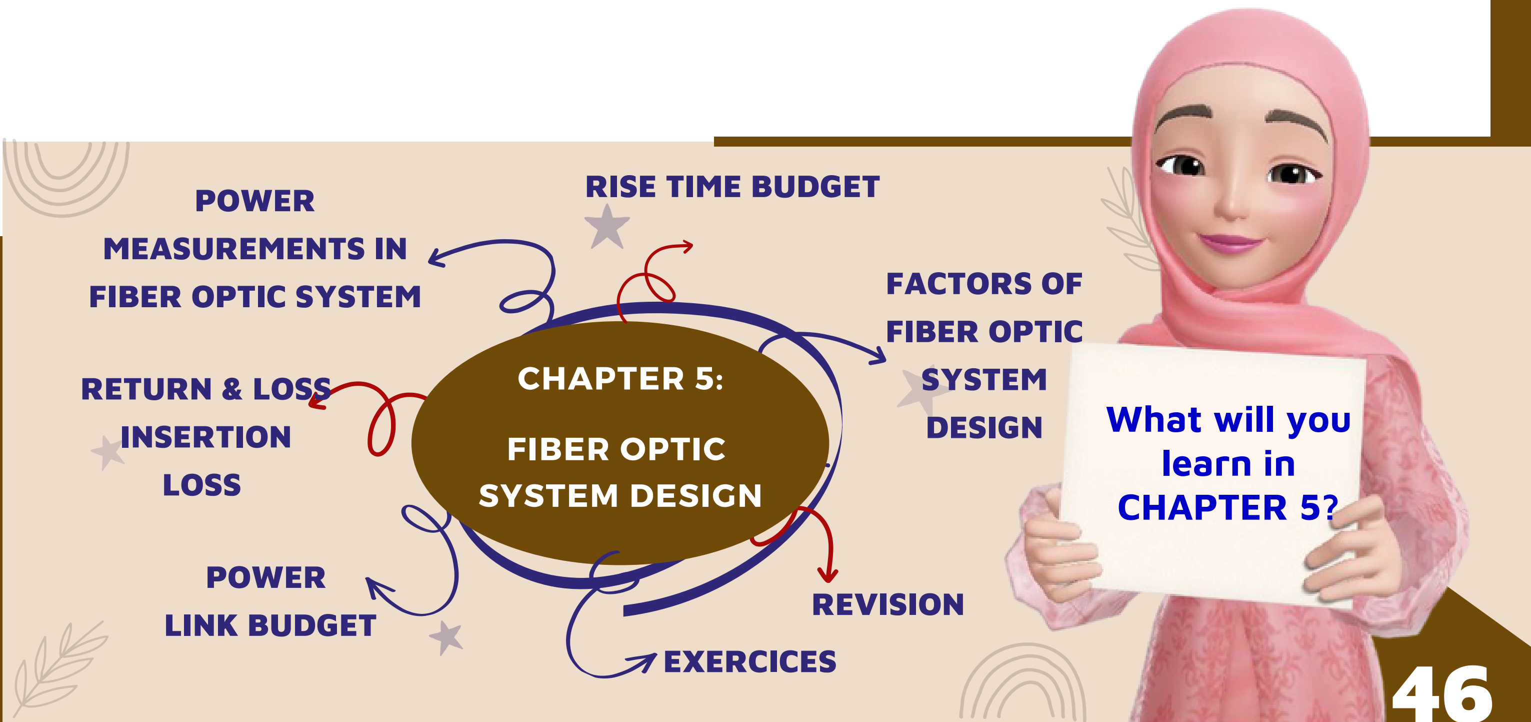
List FOUR (4) types of Fiber-in-the Loop and explain ONE (1) type of it.

CHAPTER 5 FIBER OPTIC SYSTEM DESIGN



INTRODUCTION

- The specialized procedures resulting in a successful installation and use of a fiber optic network are referred to as fiber optic network design.
- Insertion loss and return loss are significant characteristics in optical fiber communication to assess the quality of interfaces between various optical fiber components.
- In optical fibers, insertion loss (IL) is the loss of light that occurs between two fixed locations.
- Return loss (RL) refers to how much power the signal loses after being reflected or reflected again.
- A link budget is a representation of all the power gains and losses a communication signal encounters while travelling via a communication medium, such as radio waves, cable, waveguide, or optical fiber from the transmitter to the receiver.
- The distribution of available optical power (launched into a particular fiber by a given source) among different loss-producing processes, such as launch coupling loss, fiber attenuation, splice losses, and connector losses.



- Tests for optical light power are carried out by using an optical power meter. The milliwatt (mW) is a unit of light power measurement. Although a more practical unit of measurement is the decibel (dB).
- Optical loss is measured in “dB” which is a relative to 1mw optical power loss (negative number)
- Absolute optical power is measured in “dBm,” can be either positive (greater than the reference) or negative (less than the reference.)
- Optical attenuation, or loss, is the weakening of an optical signal as it travels through an optical fiber or other optically-transparent media. There are two standard units of measurement:
  - **Attenuation in a fiber optic cable**, caused by things like absorption and scattering, is often measured in dB/km.
  - **Attenuation** (in dB loss) caused by **each individual element**, such as splitters/couplers, WDMs, connectors, mechanical and fusion splices, etc.
- The attenuation of optical cables and the sensitivity of photodetectors are measured using the following units:
  - dB stands for decibels, while dBm is the decibel level relative to one milliwatt.

ATTENUATION

- When a light beam (or signal) travels a certain distance across a transmission medium, it loses intensity and amplitude, which is known as attenuation in fibre optics.
- Losses in light may be measured using this method.
- Is defined by the ratio of optical input power to optical output power:

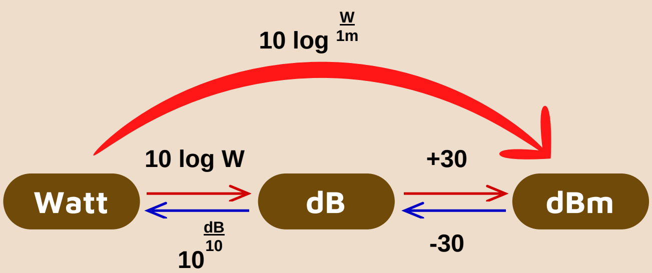
Table 5.1: Attenuation in single mode fiber optic

OS2 fiber	OS1 fiber	Wave lenght
0.4dB/km	1dB/km	1310 nm
0.3dB/km	1dB/km	1550 nm

Table 5.2: Attenuation in multi mode fiber optic

OM fiber	Wave lenght
3.5 dB/km	850 nm
1.5 dB/km	1300 nm

IMPORTANT FORMULA



Watt to dB

$$P_{(dB)} = 10\log_{10}\left(\frac{P_{out}}{P_{in}}\right)$$

Watt to dBm

$$P_{(dBm)} = 10\log_{10}\left(\frac{P}{1mW}\right)$$

Watt to dBW

$$P_{(dBW)} = 10\log_{10}\left(\frac{P}{1W}\right)$$

ATTENUATION

$$\alpha L = 10\log_{10}\left(\frac{P_{out}}{P_{in}}\right) \text{ dB}$$

$$\alpha = \frac{10\log_{10}\left(\frac{P_{out}}{P_{in}}\right)}{L} \text{ dB/km}$$

EXAMPLE 5.1:

Convert 1W and 1mW to dB and dBm

SOLUTION:

$$P_{(dB)} = 10\log_{10} W = 10\log_{10} 1 = 0dB$$

$$P_{(dBW)} = P_{(dB)} = 0dBW$$

$$P_{(dBm)} = P_{(dB)} + 30 = 0 + 30 = 30dBm$$

$$P_{(dB)} = 10\log_{10} W = 10\log_{10} 1m = -30dB$$

$$P_{(dBW)} = P_{(dB)} = -30dBW$$

$$P_{(dBm)} = P_{(dB)} + 30 = -30 + 30 = 0dBm$$

EXAMPLE 5.2:

Convert 500W to dB, dBW and dBm. Also find the attenuation of

SOLUTION:

$$P_{(dB)} = 10\log_{10} W = 10\log_{10} 500 = 26.99dB$$

$$P_{(dBW)} = 10\log_{10} \left(\frac{P}{1W}\right) = 10\log_{10} \left(\frac{500}{1W}\right) = 26.99dBW$$

$$P_{(dBm)} = 10\log_{10} \left(\frac{P}{1mW}\right) = 10\log_{10} \left(\frac{500}{1mW}\right) = 56.99dBm$$

EXAMPLE 5.3:

1mW of optical power is released into a 100m long optical fiber. Determine the fiber attenuation in decibels if the output power is 0.3mW.

SOLUTION:

$$\alpha = \frac{10\log_{10} \left(\frac{P_{out}}{P_{in}}\right)}{L} = \frac{10\log_{10} \left(\frac{0.3mW}{1mW}\right)}{0.1km} = 52.28 \text{ dB/km}$$

RETURN LOSS:
Also known as Reflection losses. It measures level of noise echoes generated by variations of impedance along the cable.

INSERTION LOSS:
A signal loss based on proportional to the frequency and the length of the cable.

RETURN LOSS

- Return loss occurs at the connecting point (ferule finish), where the fiber optic light is reflected back.
- The lower the reflection and the better the connection, the larger the return loss.
- Types of ferule finish:
  - PC (physical touch)
  - UPC (ultra physical contact)
  - APC (advanced/angle physical contact)

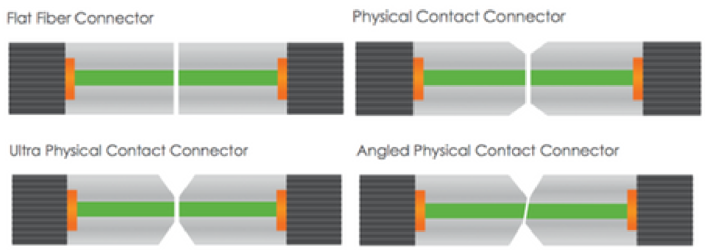


Figure 5.1: Types of ferule finish

Figure 5.2: Return loss of ferule finish

INSERTION LOSS

- When a fiber optic component is inserted into another one to establish a fiber optic connection, there is a loss of fiber optic light.
- Absorption, misalignment, or an air gap may cause insertion loss.
- Insertion loss value should be minimized as much as feasible.
- Insertion loss for fiber optic components is typically 0.2dB, but may be as low as 0.1dB upon request.

Insertion Loss (IL)

- **P1 = Power through connected fiber (Pin mW)**
- **P2 = Power through original fiber (Po mW)**
- **Insertion loss is equal to around 3 dB for a 50% reduction in power**

DID YOU KNOW?

FORMULA: Loss in Fiber Optic

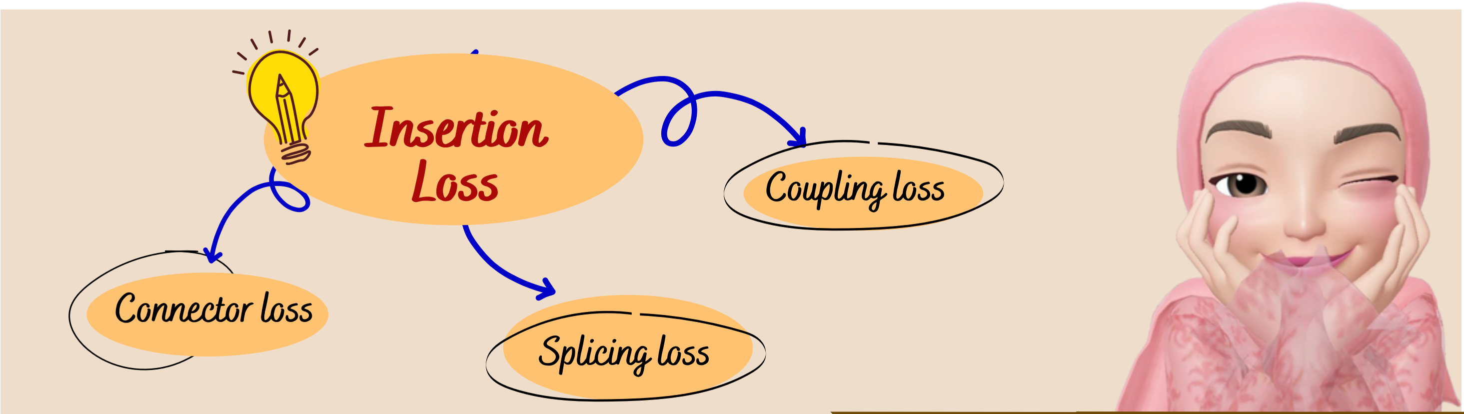
Return Loss

$$Loss_{(dB)} = 10\log_{10}\left(\frac{P_{out}}{P_{in}}\right) \quad \text{..... Equation 1}$$

$$P_{\frac{dB}{km}} = \frac{Loss_{dB}}{Fiber\ Length\ (km)} \quad \text{..... Equation 2}$$

Insertion Loss

$$IL_{(dB)} = 10\log_{10}\left(\frac{P_2}{P_1}\right)$$

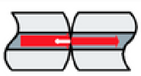
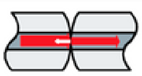
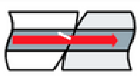


DID YOU KNOW?

CONNECTOR LOSS

- This may be due to a poor state of the connection, such as:
  - Dirt and dust surrounding the core of the cable.
  - A defect in the core of the fiber.

Table 5.3: Types of connector finish

PC	UPC	APC
Polished Convex	Ultra Polished Convex	Angled Polished Convex
Return Loss >40dB	Return Loss >50dB	Return Loss >60dB
		

COUPLING LOSS

- In the fiber optic system, the fiber coupler will function as a loss. For coupling two fiber cables, use a fiber coupler. Coupling loss refers to the little signal loss that occurred during this coupling procedure in the fiber optic system.

SPLICING LOSS

- Splicing of optical fibers is a technique used to join two optical fibers.
- There are 2 methods of splicing, mechanical or fusion. Both methods provide much lower insertion loss compared to fiber connectors.
- The fusion splice loss may be divided into two categories:
  - **INTRINSIC** - variations in optical properties based on fiber core diameter and numerical aperture.
  - **EXTRINSIC** - refers to defect of splicing occur due the misalignment between two cores or deformation at the splice.
- The acceptable loss in splicing
  - Fusion splicing ≤ 0.1 dB per splice
  - Mechanical splicing ≤0.5 dB per splice

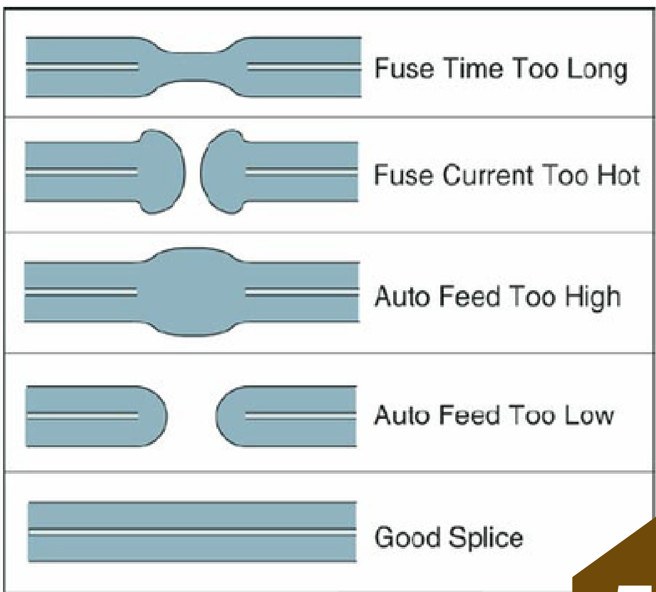
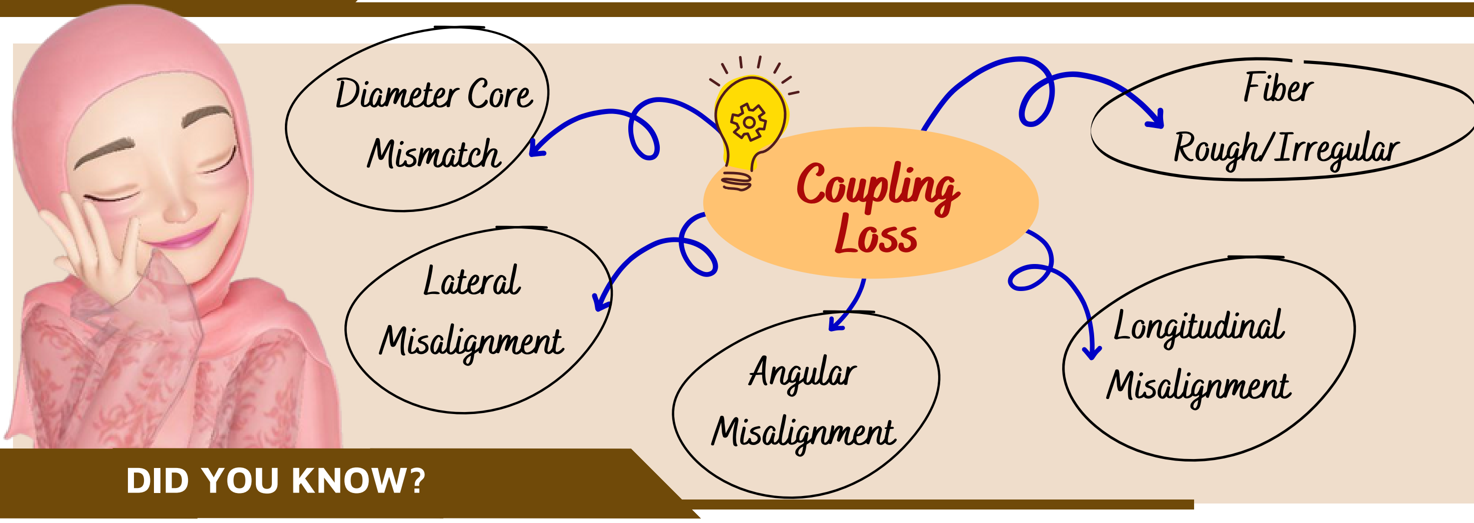


Figure 5.3: Fiber end condition of splicing



DID YOU KNOW?

DIAMETER CORE MISMATCH

- The diameter of the core and cable of two cables that are coupled/connected must be the same.
- Light propagation will be affected by a mismatch between the diameter of the cable core and the diameter of the cable.

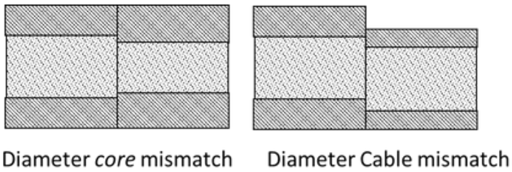


Figure 5.4: Diameter core mismatch between two cores

ANGULAR MISALIGNMENT

- The fibre is assembled with a significant misalignment of the angle at which it was cut.
- Outside the centre, light may be bent.

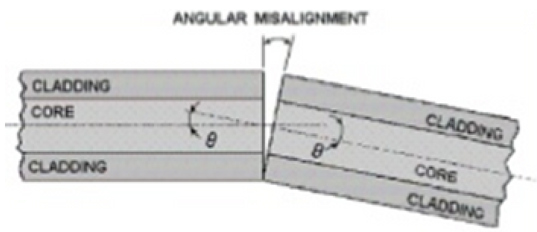


Figure 5.5: Angular misalignment

FIBER ROUGH/IRREGULAR

- Due to the fibers' rough and irregular ends, light was refracted outside of the fiber core when they were cut.

LATERAL MISALIGNMENT

- Depending on how the fiber is misaligned laterally, light may be refracted outside the fiber core or reflected inside it.

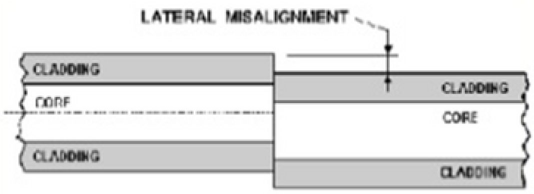


Figure 5.6 Lateral misalignment

LONGITUDINAL MISALIGNMENT

- This loss is also referred to as the separation of the fiber end in certain circles.
- The light was able to spread beyond the core, which reduced the amount of light that was transmitted.

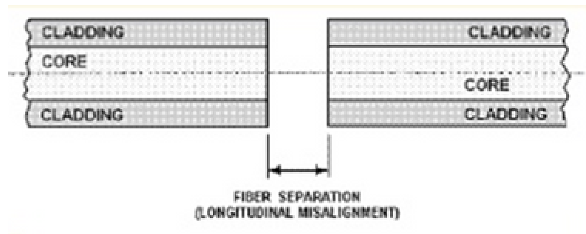


Figure 5.7: Longitudinal misalignmnet

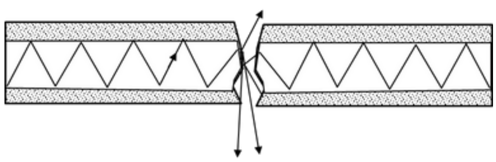


Figure 5.8: Fiber rough or Irregular ends

- The difference between the minimum transmitter output and the minimum receiver sensitivity is known as the power budget.
- A link's power budget defines the amount of optical power that may be used to compensate for link losses.

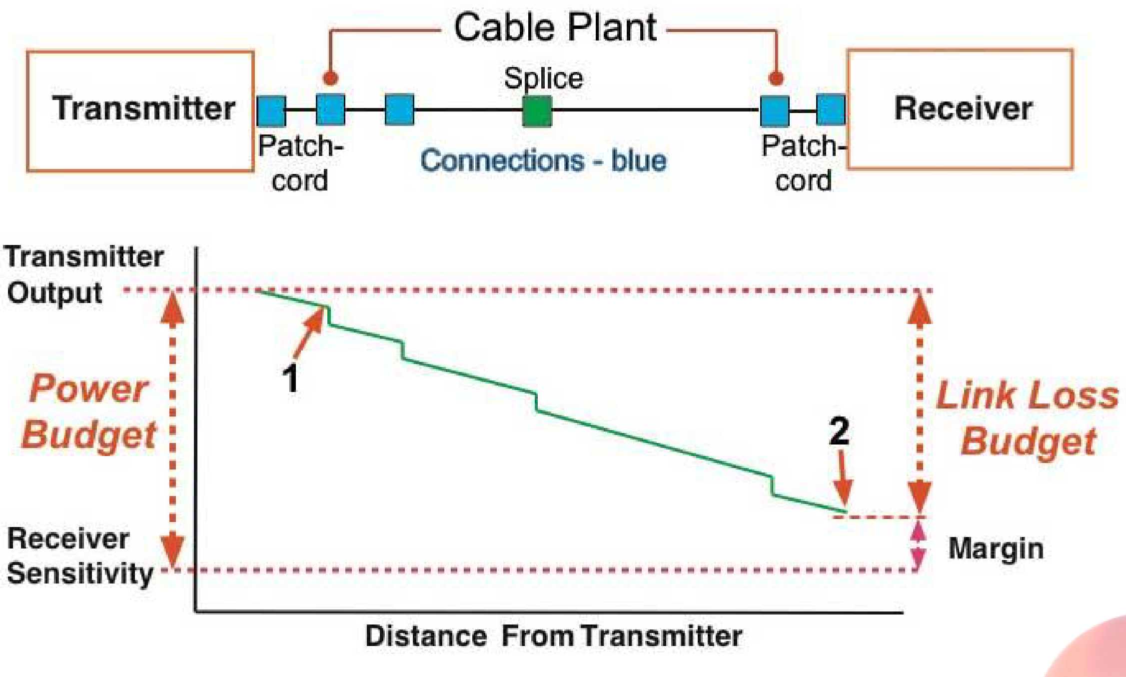


Figure 5.9: Power link budget design

IMPORTANT FORMULA

POWER BUDGET

$$P_B = P_{TX} - P_{RX}$$

Power Budget Requirement:

$$P_B = P_{TX} \geq P_{RX}$$

POWER LINK BUDGET DESIGN

$$P_{TX} = P_{RX} + T_{LL} - T_{GAIN} + P_{MARGIN}$$

$$P_{RX} = P_{TX} - T_{LL} + T_{GAIN} - P_{MARGIN}$$

TOTAL LINK LOSS

$$T_{LL} = \sum \text{Connector Loss} + \sum \text{Splicing Loss} + \text{Fiber Link Loss}$$

where:

P_{TX} – Range of optical power (transmitter) at the input of the optical link given in dBm.

P_{RX} – Range of sensitivity of the photo-detector (receiver) at end of the optical link -given in dBm.

T_{LL} – Total loss of the passive components of the optical link, i.e. attenuation of the fiber and optical connectors/splices -given in dB.

T_G – Total gain of optical amplifiers in the path (dB)

P_M – Safety margin: Range 3 dB to 6 dB

EXAMPLE 5.4:

Design a fiber optic system, end to end link from Politeknik Port Dickson to Lukut based on information below. Your answer should also contain ONE (1) factor that can be used to optimize system performance.

Distance : 22km
Transmitter output power : -30dBm
Number of splicing : 3
Splicing loss : 0.1dB
Attenuation coefficient : 0.03dB/km
Number of connectors : 3
Connector loss : 1dB
Receiver acceptable power: -32dBm
Power margin : 4dB

SOLUTION:

Fiber loss = Attenuation x length
= 0.03dB/km x 22km
= 0.66dB

Splice loss = 3 x 0.1dB
= 0.3dB

Connector loss = 3 x 1dB
= 3dB

Total loss = Fiber loss + Splice loss + Connector loss + Power margin
= 0.66dB + 0.3dB + 1dB + 4dB
= 5.96dB

Pout > Pmin
Pout = Pin – Total loss
= (-30dBm) – (5.96dB)
= -24.04dBm

-24.04dBm < -32dBm, therefore this system is not adequate/good to be built.

To enhance the performance of the system, add another amplifier to reduce the loss.

POWER BUDGET:
The maximum allowable loss is determined by the Ratio of PT/PR given in dB.

RISE TIME BUDGET:

- An easy way to estimate the dispersion limit of an optical link is to conduct a rise time budget study.
- Risetime budget includes the following:
  1. Risetime of the source, T_S
  2. Risetime of the fiber (dispersion), T_F
  3. Risetime of the amplifier, T_A
  4. Risetime of the detector, T_D
- Tx and Rx Rise Time, is normally given by manufacturer.

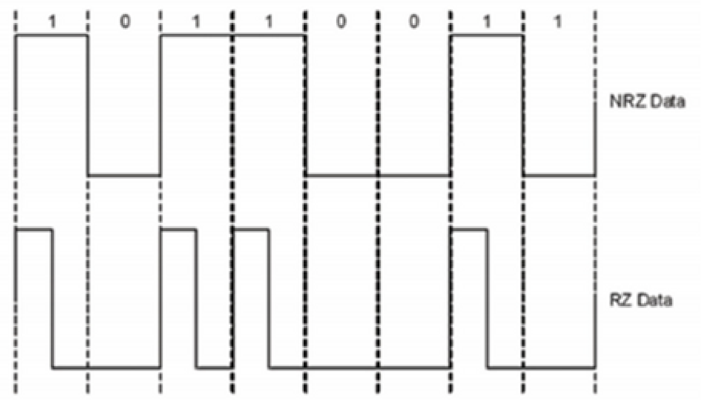
Rise Time Budget (Tsys):

Non-return-to-zero **(NRZ)**

$$T_{sys} = \frac{0.7}{B_T}$$

Return-to-zero **(RZ)**

$$T_{sys} = \frac{0.35}{B_T}$$



Rise Time Budget Requirement:

$T_{sys} \leq$ **0.7 x Pulse Width (PW)**

IMPORTANT FORMULA

Rise time budget (Tsys):

$$T_{sys} = 1.1\sqrt{T_S^2 + T_F^2 + T_D^2 + T_A^2}$$

$$T_{Fiber} = D \times \Delta\lambda \times L$$

Where :

D	=	Dispersion Coefficient (psnm^{-1}km^{-1})
$\Delta\lambda$	=	Linewidth
L	=	Fiber Length

EXAMPLE 5.5:

In order to function across an 8 km length without repeaters, an optical connection must be built. The components' respective rising times are:

- Source: 8ns
- Fiber: Intermodal 5 ns/km, Intramodal 1 ns/km
- Detector: 6ns

Estimate the highest bit rate that can be sent across the network using NRZ coding based on system risetime factors.

SOLUTION:

$$T_{sys} = 1.1\sqrt{T_S{}^2 + T_F{}^2 + T_D{}^2}$$
$$= 1.1\sqrt{8^2 + [(8x5)^2 + (8x1)^2] + 6^2}$$
$$= 46.2\text{ns}$$

Max bit rate: $B_{T(max)} = \frac{0.7}{T_{syst}}$

$$= \frac{0.7}{46.2ns} = 15.2\text{Mbps}$$

EXAMPLE 5.6:

The following requirements are provided for an optical communication system:

- Laser: λ = 1.55µm, Δλ = 0.15nm, power = 5dBm, tr = 1.0ns
- Detector: tD = 0.5ns, sensitivity = -40dBm Pre-amp: t A = 1.3ns
- Fiber: total dispersion (M+Mg) = 15.5 psnm-1km-1, length = 100km, α = 0.25dB/km
- Source coupling loss = 3dB
- Connector (2) loss = 2dB
- Splice (50) loss = 5dB
- System: 400 Mbps, NRZ, 100km

Demonstrate via appropriate methods that the link's component selection is appropriate.

SOLUTION:

For risetime budget:

System budget, T_{syst}

$$B_{T(max)} = \frac{0.7}{T_{syst}}$$

$$T_{syst} = \frac{0.7}{B_{T(max)}} = \frac{0.7}{(400\ x\ 106)} = 1.75ns$$

T_s = 1.0ns

$\boldsymbol{T_{Fiber} = D \times \Delta\lambda \times L}$

T_F = (15.5 psnm^{-1}km^{-1}) x (0.15nm(x (100km)
= 0.23ns

T_D = 0.5ns

T_A = 1.3ns

$$\boldsymbol{T_{sys} = 1.1\sqrt{T_S{}^2 + T_F{}^2 + T_D{}^2 + T_A{}^2}}$$

$$T_{sys} = 1.1\sqrt{T_S{}^2 + T_F{}^2 + T_D{}^2}$$
$$= 1.1\sqrt{1.0^2 + 0.23^2 + 0.5^2 + 1.3^2}$$
$$= 1.9\text{ns}$$

- **For a good reception of signal**
  $T_{sys} \leq$ 1.75ns

This system, T_{sys} =1.9ns
1.9ns ≥ 1.75ns

So, Bad Rise Time Budget

In order to make sure that the receiver receives adequate light, numerous things must be taken into account. The entire system won't function properly without the correct amount of light.

Table 5.4: Factors of fiber optic system design

SYSTEM FACTOR	CONSIDERATION
System structure	Typically point–to-point link
Transfer Mode / Source Type	• LED – Multimode (MM) • LASER – Multimode or Single mode (SM)
Detector type	PIN photodiode or APD photodiode
Information capabilities (modulation Code)	Coding technology – WDM, CWDM, DWDM
Operational wavelength	• MM – 850nm, 1310nm • SM – 1310nm, 1550 nm
Transmission distance	System Complexity Increases with Transmission Distance
Fiber loss factor	• Fiber loss generally has the greatest impact on overall system performance. • The fiber strand manufacturer provides a loss factor in terms of dB/km
Type of fiber optic	• Single mode (SM) or Multimode (MM) • Most SM fibers have a loss factor of between 0.25 (@ 1550nm) and 0.35 (@ 1310nm) dB/km. • MM fibers have a loss factor of about 2.5 (@ 850nm) and 0.8 (@ 1310nm) dB/km.
Number and types of splices/connector	• Mechanical splice loss is generally calculated in a range of 0.7 to 1.5 dB per connector. • Fusion splices are calculated at between 0.1 and 0.5 dB per splice. • Because of their limited loss factor, fusion splices are preferred.
Receiver Sensitivity	• The ability of a fiber optic receiver to see a light source. A receiving device needs a certain minimum amount of received light to function within specification. • Receivers are rated in terms of required minimum level of received light such as -28dBm.
Margin	• This is an important factor. A system can't be designed based on simply reaching a receiver with the minimum amount of required light. • The light power budget margin accounts for aging of the fiber, aging of the transmitter and receiver components, addition of devices along the cable path, incidental twisting and bending of the fiber cable, additional splices to repair cable breaks, etc. • Most system designers will add a loss budget margin of 3 to 10 dB

FIBER OPTIC SYSTEM DESIGN

ATTENUATION / LOSS IN FIBER OPTIC

RETURN LOSS

- PC (physical contact)
- UPC (ultra physical contact)
- APC (angle physical contact)

INSERTION LOSS

- Diameter core mismatch
- Longitudinal misalignment
- Lateral misalignment
- Angular misalignmnet
- Fiber rough/irregular

POWER LINK BUDGET

POWER BUDGET

$P_B = P_{TX} - P_{RX}$

POWER LINK BUDGET DESIGN

$P_{RX} = P_{TX} - T_{LL} + T_{GAIN} - P_{MARGIN}$

RAISE TIME BUDGET

RISE TIME BUDGET (TSYS):

$$T_{sys} = 1.1\sqrt{T_S{}^2 + T_F{}^2 + T_D{}^2 + T_A{}^2}$$

$$T_{Fiber} = D \times \Delta\lambda \times L$$

Remember, you must follow the requirement of Power Budget & Rise Time Budget!

Power Budget Requirement:

$P_B = P_{TX} \geq P_{RX}$

Rise Time Budget Requirement:

$T_{sys} \leq 0.7 \times$ Pulse Width (PW)

EXERCISE 5.1:

A 5.4km fiber optic system from Taiping to Bukit Merah has to be designed by you as an engineer for a Malaysian telecommunications business. An attenuation coefficient of 2.5 dB/km for fiber optic cables and a transmitter output power of -22 dBm are required for the system to function properly. The receiver's lowest permissible power (receiver sensitivity) is -34 dBm, and the system additionally includes two connection losses of 0.25 dB each. Only a 4dB power margin should be allowed by the system. Design the end-to-end connection based on the provided information, taking into account the estimate of total link loss and the optical power budget. In order to maximize system performance, the design should assess system performance based on the power budget calculation and recommend THREE (3) system factor considerations.

EXERCISE 5.2:

The output power of a transmitter is 0.1mW. The insertion loss of two connectors in fiber is 0.2 dB, and the attenuation of fiber for a length of 1 km is 3.5 dB/km. There is one 0.1dB fiber splice in the link. The minimum power that the receiver can handle (its sensitivity) is -20dBm. The designer has left a margin of 4dB. Assuming that the design has a Hub (Tx/Rx) that connects to a Patch Panel and a Wall Outlet through a fiber optic cable. Patch Cable is also used to link the wall outlet to the computer. Make a budget for fiber optic link loss based on the information given. Figure out how much power was lost in the fiber optic link and how much power was received in total. Based on an assessment, make a prediction about your design and choose the right type of fiber optic and light source that will be utilized in this system.

EXERCISE 5.3:

A 17km fiber optic infrastructure, seen in Figure 5.10, will be built between Sri Kembangan and Putrajaya. In order to complete the end-to-end link design, you must use the data shown in Table 5.3 to do the necessary calculations, such as those needed to determine the total link loss and the optical power budget. There should be no more than a 3dB power margin in the system. As part of your response, please provide a ONE (1) factor that may be utilized to improve the efficiency of the system.

Table 5.3: Information of gain & loss in power link budget

Connector loss	0.15dB
Amplifier gain	12dB
Splice loss	0.1dB
Attenuation Coefficient, α	0.3dB/km

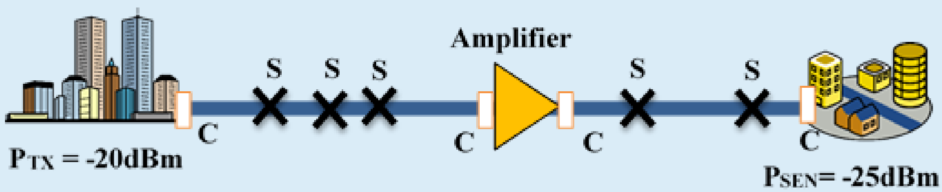


Figure 5.10: End-to-end link of fiber optic

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Fundamental Concepts of Fiber Optic

THANK YOU

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